

EXPLOITING WIND POWER FOR THE PRODUCTION OF ELECTRICITY

M. Johansson

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| 16. Abstract This report deals with the economic, energy-economic and environmental issues involved in any prospective exploita- tion of wind power intended to cover a minor part -- e. g., 10% -- of Denmark's consumption of electricity. The chief basis for the calculations involved is the 200 kW experimental windmill built at Gedser in 1956-57, which ceased to produce electricity in 1967. However, in explor- ing the ramifications of making Denmark partially depen- dent on wind energy power, estimates are made on the basis of projected larger series of mills of the Gedser type. Wind mill projects abroad, such as at Vattenfall, NSF and NASA, are also discussed, as is Denmark's dependence on power from Sweden and Germany. | | | |
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Summary

The report deals with the economic, energy-economic and environmental issues involved in any prospective exploitation of wind power intended to cover a minor part -- e.g., 10% -- of Denmark's consumption of electricity.

The report is based on a reevaluation of construction costs and production as far as windmills are concerned, taking its point of departure in the 200 kW experimental windmill at Gedser, which was constructed in 1956-57 under the auspices of the Committee on Wind Power of the Danish Power Plants Society. This windmill ceased to produce electricity in 1967.

The report deals briefly with a few investigations of current interest which have been carried out in other countries, concerning the exploitation of wind power for the production of electricity.

A more detailed description of the Gedser mill is presented in an appendix. Another appendix deals with the question of the windmills' output value.

The results of the investigation are brought together in the conclusion towards the end of the report.

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EXPLOITING WIND POWER FOR THE PRODUCTION OF ELECTRICITY

M. Johansson

Introduction

The rapid price increases in fossil fuels in the past year, /1 combined with the observed difficulties in delivery, have created an increased interest in alternative sources of energy, including wind power. Wind power and solar energy, constitute Denmark's sole domestic sources of energy of any consideration.

Wind power has been used in the Danish countryside ever since around the year 1200, when windmills were introduced to the country. The windmill, which exploited the power of the wind directly in performing such tasks as grinding grain, gained extensive popularity as time wore on, and in the second half of the last century there were between 6,000 and 8,000 grain-grinding windmills here at home.

The exploitation of wind power for the production of electricity began towards the end of the last century, at Professor Poul la Cour's in Askov. In 1892, la Cour constructed his first electricity-producing experimental mill. At the outset, the electricity was used for electrolysis of water into hydrogen and oxygen, which in turn were used for illumination, but later la Cour switched to using the electricity in charging accumulators.

In 1904, the Danish Wind Electricity Society was formed for the purpose, among other things, of providing guidance in the construction of electrical power plants, primarily within the area of wind power. By 1908, 72 wind power plants had been built -- each with a capacity of 10-20 kW and with a petroleum or diesel engine for auxiliary supply -- and the number rose to 120 by the end of the First World War in 1918. In the years between the two world wars the number of wind power plants decreased, but during the Second World War they again gained a certain degree of popularity, so that by 1943 there were supposedly about 70 of these 10-20 kW mills.

The energy supply situation during the Second World War was also the reason why F. L. Smidth in 1940 started work on rapid-moving, direct current windmills. (Wingtip speed was 5-6 times the wind speed, compared with the 2-3 times wind velocity obtained by la Cour's mills with adjustable vanes). All told, F. L. Smidth built 18 windmills during the war, with a collective power of about 800 kW.

In 1947, upon the initiative of department head engineer J. Juul, the SEAS began an inquiry into the use of wind power for the production of alternate current. As a part of these

investigations, the SEAS in 1950 built an experimental mill with a 13 kW capacity at West Egesborg, and in 1952 F. L. Smidth's direct current mill at Bogø was taken over and rebuilt into one aimed at the production of alternate current (45 kW). /2

Because the work being done by the SEAS on windmills also was of interest outside the company, the DES (Danish Power Plants Society) in 1950 named a wind power committee with representatives from the power plants, the manufacturers of wind engines, the Ministry for Work and Social Concerns, and from the ATV. In 1956-57, this committee had constructed the 200 kW capacity Gedser mill.

On the basis of experiences obtained from the Gedser mill, the Wind Power Committee in 1962 published its deliberations (Ref. 1), which said in conclusion (in extenso):

- a) The Gedser mill is operating satisfactorily.
- b) It is efficient to produce alternate current directly to an existing powernet.
- c) The cost price of wind power electricity corresponds to the cost price for steam power electricity produced by means of fuel, which costs 17-19 kr/Gcal (the 1962 price for fuel was 8-9 kr/Gcal).
- d) Wind power may be of value in replacing the importing of fuel, and may be a reserve which could be drawn upon in situations when fuel is scarce. However, the necessary investment would be big enough so that the undertaking of such a project for these reasons alone would seem inappropriate.
- e) The construction of wind power plants may on the whole be done with Danish labor and could to a considerable degree be adjusted to the prevailing employment situation.
- f) There is a good possibility that Danish industry would have a share in the supply of wind power plants to developing countries.

With the publication of its deliberations, the Wind Power Committee ceased to exist, making over the Gedser mill to the SEAS, which continued running it until 1967. At that time, the mill's production was stopped, because for some years the expenses incurred in running and maintaining the mill had been greater than the value of the power produced.

2. The Gedser Mill

A brief summary of the construction of the Gedser mill may be found in Appendix A. Only the most important data will be given here:

Number of wings: 3
Wing span diameter: 24 m
Wing span area: 450 m²
Wing tip speed: 38 m/sec
No. of wing revolutions per minute: 30
Generator: 200 kW, asynchronous, 8-poled, 750 rev./min
Generator slip from 0 to full load: 1%

The mill is self-starting at wind speeds of 5 m/sec and yields 200 kW at a wind velocity of 15 m/sec when the temperature of the air is 5°C.

The transmission between rotor shaft and generator takes place by means of a double chain drive with a conversion ratio of 1:24. The mill is 25 m tall.

Figures 1 and 2 show how the mill looks on the outside.

3. An evaluation of the circumstances involving a "Gedser Mill" constructed today. /4

This section is devoted to an evaluation of the construction costs involved in building a "Gedser Mill" today, with no changes made in the design. On the basis of these construction costs and the energy produced, an economic and energy-economic comparison will be made between wind power and steam power plants.

3.1. Construction costs

The anticipated costs (not including sales tax) involved in constructing a series of about 100 "Gedser mills" have been evaluated in cooperation with such firms as:

The South Jutland Machine Factory (Sønderjyllands Maskinfabrik) -- a division of the South Jutland High Tension Works (Sønderjyllands Højspændingsværk) -- which manufactures components for power plants and constructs electrical power nets.

The engineering firm of B. Højlund Rasmussen, which serves as consultants for a number of constructions designed to carry heavy loads, such as bridges. In the past, this firm planned the Gedser mill's tower.

The engineering firm of Per Udsen, Grenå, which in its capacity of subordinate supplier for the SAAB factories produces tail sections made of aluminum for Draken fighter planes, and which also makes transformer huts.

3.1.1. Tower, etc.

The costs involved in constructing the tower, which is made of stressed concrete, have been evaluated in part by the

engineering firm of B. Højlund Rasmussen, and in part by the South Jutland Machine Factory, with the assistance of Larsen & Nielsen Inc., which built the Gedser mill's tower.

The two firms estimate that the tower would cost 190,000.- kr. (B. Højlund Rasmussen's estimate) or Kr. 215,000. if one tower were to be built.

The construction of a greater number of towers, such as 100, has been estimated by the South Jutland Machine Factory to cost a total of ca. Kr. 300,000. including the engine hut.

Building site

The size of the Gedser mill building site was 1200 m². A corresponding site in a rural zone today would cost a maximum of Kr. 10,000.

Soil testing

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According to the Geotechnical Institute, a geotechnical investigation for an electricity producing mill of the Gedser type would cost from 3,000 to 15,000 kroners, depending on the soil conditions.

3.1.2. Engine hut, etc.

The South Jutland Machine Factory estimates that the cost of engine hut, propeller hub, chain drive, holding brake, hydraulic brake lifter, etc, including the cost of mounting, would be about Kr. 210,000 for a single mill. If a series of 100 mills were made, these components plus the tower are estimated at about Kr. 300,000 per mill.

3.1.3. Wings

The mill wings are the hardest component to estimate, because technological developments have opened the way for many new manufacturing possibilities in this area.

Based on the price listed on the invoice for the Gedser mill's wings, the cost today may be estimated at perhaps 150,000-200,000 kroners for one set of wings (but it is uncertain whether the SEAS, which built the wings, included all the costs on the invoice.)

The engineering firm of Per Udsen has estimated that the cost of the wings -- covered with aluminum sheeting -- would be about Kr. 240,000 per set if 100 sets were produced. If only a single set were produced, the cost would be well over Kr. 300,000.

Contact has also been made with the firm of Hamilton Standard, which produces helicopter wings, among other things, but this

firm has not been able to give an estimated cost for the mill wings.

In the following calculations the cost of the wings has been set at Kr. 300,000 for a single set and Kr. 240,000 per set in a series of 100 sets.

3.1.4. Generator, etc.

The estimated costs of generator, transformer, distribution equipment, relays, meters, etc, are judged by the Information Section of the Danish Power Plants Society to be about Kr. 150,000 when constructing a single mill (the generator alone costs about half of that sum). The cost per mill in a series of 100 mills is /6 estimated to be about Kr. 130,000.

3.1.5. Planning

The prices quoted above include the costs of planning new "Gedser mills" based on the construction of the mill at Gedser.

However, the prices do not include measuring wind power distribution in the manner necessary for optimal production on the part of a given mill. Taking such measurements in a number of selected locations around the country would probably cost around 500,000-750,000 kroner or -- distributed among 100 mills -- on the order of Kr. 10,000 per mill.

3.1.6. Total construction costs

Below, estimated 1974 costs are compared with the actual costs involved in the mill at Gedser (Ref. 1, p. 32).

| | <u>Cost of Gedser mill (1956-57)</u> | <u>Estimated costs of a 1974 "Gedser mill"</u> | |
|--|--|--|----------------------|
| | | <u>For 1 mill</u> | <u>For 100 mills</u> |
| Tower (incl. soil testing and building site) | 76,400 | 210-235,000 | |
| Engine hut (incl. mounting) | 75,000 | | 320,000 |
| Wings and propeller hub | 44,136 | 210,000 | +240,000 |
| Chain drive, holding brake, hydraulic brake lifter, etc. | 20,424 | + | |
| Generator, transformer, distribution system, etc. | 56,766 | 300,000 | |
| Total for Gedser mill | 272,725 | 150,000 | 130,000 |
| Planning | 47,693 | | 10,000 |
| Total | 320,693 | 870-895,000 | 700,000 |

Thus, a Gedser mill built in 1974 is estimated to cost about 175% more than the mill built at Gedser in 1956-57. In building a greater number (100) of mills, the cost should be reduced by about 20%, resulting in a total cost of Kr. 700,000.

The rated output of the Gedser mill was 200 kW, and the cost per kW thus becomes $700,000/200 = \text{Kr. } 3,500/\text{kW}$ for a larger series.

3.2. Energy production

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As mentioned in Appendix A, Section A.5, the normal annual production of the Gedser mill is estimated at about 400,000 kWh.

At the same time, the Gedser mill was put into operation, the Wind Laboratory (under the auspices of Dr. Phil. et Techn. Martin Jensen) began the wind measurements described in Section A.5. According to Dr. Jensen, these wind measurements showed that the Gedser mill did not have ideal gears. With proper gearing of the Gedser mill, it is supposed that annual production may be increased by about 16% to about 460,000 kWh.

On the basis of p. 15 of Item 1 in the Bibliography, it is thus possible to calculate the following energy production for variously located Gedser mills:

| | |
|---|--|
| Gedser (near the optimal location in Denmark): | 460,000 kWh/year |
| Torsminde (optimal placement on the Jutland peninsula): | $460,000 \cdot \frac{49}{42} = 540,000 \text{ kWh/year}$ |

| | |
|--|--|
| Tune (representative of the best location in the interior of the country): | $460,000 \cdot \frac{29}{42} = 320,000 \text{ kWh/year}$ |
|--|--|

At a height of 25 m above ground level, the annual energy production per power unit (i.e., the amount of time the installed power is used) is:

| | |
|------------|---|
| Gedser: | $460,000 \text{ kWh}/200 \text{ kW} = 2,300 \text{ kWh/kW}$ |
| Torsminde: | $540,000 \text{ kWh}/200 \text{ kW} = 2,700 \text{ kWh/kW}$ |
| Tune: | $320,000 \text{ kWh}/200 \text{ kW} = 1,600 \text{ kWh/kW}$ |

and the yield per m^2 of surface area becomes:

| | |
|------------|--|
| Gedser: | $1,000 \text{ kWh}/\text{m}^2, \text{ year}$ |
| Torsminde: | $1,200 \text{ kWh}/\text{m}^2, \text{ year}$ |
| Tune: | $700 \text{ kWh}/\text{m}^2, \text{ year}$ |

or about 28% of the wind's total annual energy contents. Theoretically a windmill can, as its maximum, use 59% of the wind's energy, so the 28% corresponds to an energy exploitation which is 47% of that which is theoretically possible.

3.2.1. The extent to which energy production is dependent upon height.

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Item 3 in the Bibliography describes a calculation of a windmill's energy production as a function of the mill's height. The calculation is based on Risø's wind measurements at heights of 7, 23, 39, 56, 72, 96 and 123 m above ground level during the ten-year period 1958-67.

This reference states that the energy production for a windmill (assuming constant effectiveness within a given area of speed, and assuming that the diameter of the propeller is small in relation to the height of the mill) for the height, h is

$$E_h = E \log h$$

in which E is the energy production at a height of 10 m.

Fig. 6 shows this relationship as well as the increase in production per additional meter of height, drawn with reference to a 25 m tall mill.

It may be seen from Fig. 6 that the percentile increase in production per additional m of height is quite small -- about 1.2% per m -- for a windmill which is 25 m tall. If the height of the mill is increased from 25 to 50, an increase in production of about 21% may be obtained (this ratio corresponds to that found between the total power of the wind at heights of 50 and 25 m, with an average 1.21, observed during the wind measurements at Gedser). An increase in annual production of about 50% demands -- if the height of the mill is the only variable -- an increase in height from 25 to 125 m.

The above assumptions regarding the mill's degree of efficiency were not met as far as the Gedser mill was concerned (Fig. 3, Curve 1). The stated relationship between energy production and height is, however, reasonably valid for a "Gedser mill" as well, provided the gearing is adjusted to the height of the mill.

3.3 The basis for an economic comparison of wind power plants and steam power plants

In Sections 3.4 and 3.5 below, an economic comparison is made between the production of electricity from a wind power plant and the production of electricity from a steam power plant. The comparison includes partly expenditures and savings, partly financing, and, finally, considerations involving the spending of foreign currencies.

Comparative expenditures and savings are listed for a windmill and a corresponding steam power production. The figures

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are based partly on annual expenditures during the write-off period and partly on the present value of total costs.

Annual expenditures consist of annual payment of principal as well as of operating costs. The payment on the principal is calculated as a fixed annual payment corresponding to the fixed payment on long-term loans. Operating costs, however, are assumed to vary with the rate of inflation and thus account for an ever increasing part of the annual total expenditures.

The current value of total costs is calculated on the basis of construction costs in the first year plus operating costs throughout the write-off period (20 years), because the latter are retrospectively discounted to the initial year with consideration given to a fixed market rate of interest.

The financing of production plants is listed in the form of a comparison between wind power and steam power, and the financial contribution to further extension of wind power production which is obtained from the net operating costs derived from wind power is calculated for a given later year.

The expenditures and savings involving foreign currencies are also calculated, as is the rate at which the expenditure of foreign currencies pays for itself.

The methods used in the economic evaluation of wind power and steam power are not tied to any particular economic situation (except with regard to interest rates and the rate of inflation, etc). In any future deliberations concerning the introduction of wind power plants it will be necessary to undertake an economic appraisal in which consideration is given to the current economic situation within the area of electrical power supply. Such an appraisal may lead to a partial alteration in the conclusion regarding economic circumstances.

The absolute value of the quantities given in the following sections is tied to a "Gedser mill" which was constructed in 1974. However, regardless of the assumed construction year for the mill, the relationship between the cost of electricity produced by wind power and the cost of electricity produced by steam power will remain unchanged, provided wages and the costs of fuel and mill construction increase at the same rate as the inflation.

3.3.1. Symbols and numerical values used

| <u>Symbol</u> | <u>Meaning</u> | <u>Numerical values</u> |
|---------------|--|---------------------------------|
| A | Specific construction costs for the windmill | 3,500 Kr/kW (see Section 3.1.7. |

| <u>Symbol</u> | <u>Meaning</u> | <u>Numerical values</u> |
|---------------|---|---|
| x) | Specific construction costs for steam power plant | Average load unit using oil as fuel (150 MW): 1,000 Kr/kW Basic load unit using coal and oil as fuel: 1,600 Kr/kW |
| C | Fuel prices | Item 2 in Bibliography uses the same C for coal and oil. For 1974 C is figured as equalling 30 Kr/Gcal. (July 1, 1974 C was equal to 40/Kr/Gcal) (Wind power will probably replace the most expensive fuel, low-sulphur oil. The price of this fuel as of July 1, 1974 was only a few percent more than the stated 40 Kr/Gcal for oil containing a larger amount of sulphur, but the difference has been considerably greater in the past.) |
| x) | Specific construction costs for the transmission net (including 60/10 kV stations) | 975 Kr/kW |
| E | The amount of time the wind-mill is used | See Section 3.2 |
| x) | The amount of time the steam power plant is used | Average load units: 4,000 h Basic load units: 7,000 h |
| N | Current value of an annuity of 1 Krone during the plants' write-off period at an interest rate of $\frac{1 + \text{market interest} - 1}{1 + \text{inflation}}$ | 1) |
| W | The windmill's annual energy production | *See Section 3.2. |

| <u>Symbol</u> | <u>Meaning</u> | <u>Numerical values</u> |
|---------------|---|---|
| α | Annual interest rate plus write-off | 1) |
| a | Expenses per energy unit for maintenance of the mill, inspection, etc. | Item 1 in the Bibliography uses the following figures: for the Gedser mill: in 1962 $a = 1 \text{ øre/kWh}$ corresponding to about 3.5 øre/kWh in 1974. For a greater number of mills, $a = 3 \text{ øre/kWh}$ (corresponding to 10-15,000 Kr/year per mill). |
| $x)$ | Operating and maintenance costs (other than fuel) for steam power plants | Average load units: 0.8 øre/kWh . Coal/oil fueled basic load units: 0.6 øre/kWh |
| d_h | Operating and maintenance costs dependent on kWh (other than fuel) for steam power plants | 0.3 øre/kWh |
| i | Annual inflation | 1) |
| n | Year, with reference to the year of construction (1974) | |
| p | Average loss in transmission from power plants to 60/10 kV stations (inclusive) | 5% |
| q | Specific fuel consumption for steam power plants | New average load units: $2,400 \text{ kcal/kWh}$ Coal/oil fueled basic load units: $2,100 \text{ kcal/kWh}$ |
| q_m | Differential value of specific fuel consumption | q_m varies during the year from $2,200\text{--}2,300 \text{ kcal/kWh}$ to $3,000\text{--}3,300 \text{ kcal/kWh}$. As an average, q_m is figured as equal to $2,600 \text{ kcal/kWh}$. |

$x)$ is used only implicitly.

Sources: Item 2 in Bibliography, NESÅ, et al.

1) Experience shows the market interest rate to be ca. 4-6% above the rate of inflation. The calculations are therefore made for the following two cases:

| <u>Market interest rate</u> | <u>4% difference (corresponding to Item 2 in the Bibliography)</u> | <u>6% difference</u> |
|-----------------------------|--|----------------------|
| | 12% | 16% |
| i | 8% | 10% |
| α | 13.3% | 16.8% |
| N | 13.9% | 12.0 |

with α and N given for a write-off period of 20 years.

In addition to the length of the write-off period, N also /12 depends mostly on the difference between the rates of interest and inflation, and only to a lesser degree on the absolute size of these two figures. With an interest rate of 18% and an inflation rate of 14%, N is thus 14.2 against 13.9 when the interest rate is 12% and the rate of inflation is 8%.

3.4. Wind power plant serving as a supplement to a steam power plant

Wind power is compared economically with steam power, because no output value is assigned to wind power, which is used in order to conserve fuel. When wind power is available, it thus replaces production at that/those power plant(s) which at a given time has the greatest marginal production costs.

It is assumed that only enough wind power plants will be constructed to cover 5-10% of the country's consumption of electricity, corresponding to about 2,000-5,000 mills the size of the mill at Gedser.

3.4.1. Expenses and savings

The annual cost of producing 1 kWh of wind power consists of interest and write-off costs for the mill:

$\frac{A}{E} \cdot \alpha$ plus the cost of maintenance and inspection etc:
a, as follows:

$$\frac{A}{E} \cdot \alpha + a \quad (3-1)$$

By feeding in 1 kWh of wind power on the 10 kV network, the power plants save (assuming that the wind energy is taken off the same 10 kV power net) 1 kWh plus transmission losses, i.e., about $\frac{1}{1-p}$ kWh (because the calculation is made with the average transmission loss, p. If only a few mills are established, the marginal losses will be saved 2 p, which makes the relationship about $2p-p = p = 5\%$ more favorable for the windmills).

The marginal costs of fuel for 1 kWh of steam power are $q_m \cdot C \cdot 10^{-6}$, and savings on maintenance etc are d_n . The production of 1 kWh of wind power thus saves steam power expenses of

$$\frac{1}{1-p} (q_m \cdot C \cdot 10^{-6} + d_n) \quad (3-2)$$

If -- as in Ref. 2 -- one calculates with the same fixed /13 annual increase in the expenditures for fuel, operation and maintenance, the expenses and savings for year n will be:

$$\frac{A}{E} \cdot x + a (1+i)^n \quad (3-3)$$

and

$$\frac{1}{1-p} (q_m \cdot C \cdot 10^{-6} + d_n) (1+i)^n \quad (3-4)$$

The retrospectively discounted value of expenses and savings per kWh of wind power (produced every year during the write-off period) will be respectively

$$\frac{A}{E} + a \cdot N \quad (3-5)$$

and

$$\frac{1}{1-p} (q_m \cdot C \cdot 10^{-6} + d_n) \cdot N \quad (3-6)$$

In Figures 7 and 8, (3-3) and (3-4) are drawn up on the basis of the values given in Section 3.3.1.

From Figure 7 (interest rate 12%, inflation rate 8%) it may be seen that wind power from a mill constructed this year will cost about 20-32 øre/kWh, depending on where in the country the mill is located, compared with the marginal price of steam power of about 8.5 øre/kWh (delivered on a 10 kV level). These prices go up during the write-off period of the mill, to about 31-43 øre/kWh for wind power and about 40 øre/kWh for steam power in twenty years. The annual expenses for wind power will balance with the marginal savings on steam power after about 15-17 years at

the locations of Torsminde and Gedser, while such a balance is not obtained during the mill's write-off period by the location at Tune.

Fig. 8 (interest rate 16%, inflation rate 10%) shows that wind power will cost about 25-40 øre/kWh in the construction year (1974) and about 42-57 øre/kWh at the end of the write-off period. Corresponding figures for the marginal steam power are about 8.5 øre/kWh and about 58 øre/kWh. Annual expenses and savings will balance after about 15-20 years, i.e., at approximately the same time as in Figure 7.

With the values listed in Section 3.3.1., the retrospectively ¹⁴discounted expenditures and savings per kWh of wind power produced each year during the write-off period (20 years) will be:

| N = 12.0 | | | N = 13.9 | | | |
|---------------------------------|--------|------|-----------|--------|------|------|
| Torsminde | Gedser | Tune | Torsminde | Gedser | Tune | |
| Expenses (3-5) | 1.66 | 1.88 | 2.55 | 1.72 | 1.94 | 2.61 |
| Savings (3-6) | | 1.02 | | | 1.18 | |
| Expenses in relation to savings | 1.6 | 1.8 | 2.5 | 1.5 | 1.6 | 2.2 |

In the stated area for N -- 12.0 to 13.9 -- the current value of the expenses is thus greater than the savings, namely about 1.5-2.5 times greater.

Figure 9 shows the function $\frac{A}{E} = f(C)$ which indicates equilibrium between the retrospectively discounted expenses for wind power and the savings in steam power. From the figure it may be seen that if the cost of fuel is 30 Kr/Gcal, wind power becomes profitable at a construction cost of 0.65-0.8 Kr. per kWh annual production, i.e., 40-50% below the construction costs for a mill at Torsminde. A windmill built at Torsminde will be profitable at a 1974 fuel price of 44-50 Kr/Gcal (fuel cost in July 1974 is about 40 Kr/Gcal), while a windmill at Gedser or Tune respectively will become profitable at a 1974 fuel price of about 50-56 Kr/Gcal and 68-76 Kr/Gcal.

3.4.2. Financing

As shown above, the windmills require very large plant investments, while operating costs, on the other hand, are very small.

Expanding the use of windmills to cover 10% of Denmark's present annual consumption (of 17 TWh) will require a plant investment of about 2200 million Kroners (ca. 3,100 mills), provided the mills are optimally located, such as at Torsminde.

Because windmills are only seen as conserving fuel, such an investment is an additional investment which only eventually corresponds to savings in fuel purchases. Any possible future decision on the establishment of windmills must therefore to a large extent depend on the employment situation and the general state of the economy.

A construction program might, for instance, comprise 500 windmills per year (350 million Kroners per year), corresponding to about 10-15% of the annual increase in consumption of electricity. With such a construction program, the windmills should cover about 5-7% of the anticipated consumption of electricity.

Annual net savings after 10 years would in this case amount to approximately 90-150 million Kroners (1974 prices), making possible the financing of the construction of about 130-210 windmills this year (assuming that the cost of the "Gedser mill" follows the rate of inflation).

3.4.3. Expenditure of foreign currency

The expenditure of foreign currency involved in the construction of a windmill is estimated -- with a good deal of uncertainty -- to be:

| | | |
|----------------------------|----------------------|---|
| Electrical equipment | ca Kr. 70-85,000 | (of which ca. Kr. 60,000 are for the generator) |
| Raw materials (steel, etc) | ca. Kr. 45-55,000 | |
| Various machine parts | ca. Kr. 20-50,000 | |
| Total | ca. Kr. 135-190,000, | or about 20-30% of the construction costs. |

(In the production of large series it is possible that the generator may be produced advantageously in Denmark, by which means the expenditure of foreign currency would be reduced to 10-20% of the construction costs.)

A windmill with an annual energy production W saves, during its write-off period, foreign currency expenditures on fuel of (retrospectively discounted) a total of

$$\frac{W}{1-p} \cdot q_m \cdot C \cdot 10^{-6} \cdot N$$

(3-7)

With the values listed in Section 3.3.1, the savings per windmill in various locations will be as follows:

| | N = 12.0 | | | N = 13.9 | | | |
|--|----------------|---------|---------|----------------|-------------|---------|--------------|
| | Tors- minde | Gedser | Tune | Tors- minde | Gedser | Tune | |
| Savings on foreign currency (3-7) | 530 | 450 | 310 | 620 | 520 | 360 | 1,000 Kr. |
| Currency expendi- tures for wind- mill | 135-190 | | | | | | |
| Resulting savings on foreign currency | 340-395 | 260-315 | 120-175 | 430-485 | 330- 385 | 170-225 | |

Thus, foreign currency expenditures of about 135-190,000 Kr. will result, during the 20 years of the write-off period, in a retrospectively discounted foreign currency saving of about 310-620,000 Kroners, corresponding to a net saving of about 120-485,000 Kroners. If only the foreign currency aspect is taken into account, an amount invested in windmills will pay for itself in the course of about 4-10 years (depending on the location of the windmill and the size of the interest rate minus inflation), and at the end of the write-off period the amount will have been paid back approximately 1.5-3.5 times over.

3.5. Wind power stations as a partial alternative to steam power plants

In Appendix B, the output value of wind power is examined. The conclusion of this investigation is that:

- 1) Seen over a period of a year, wind power has a certain, but small, output value. The power derived from a 200 kW windmill would probably be about 20 kW.
- 2) During some periods the connection with other countries will be greater than what is necessary for the purposes of maintaining reserves. During such periods the foreign connection may in part compensate for the unreliability of wind power. This is the case for a few years ahead

at Elsam, where the maximum power to be derived from a 200 kW windmill is estimated to be about 60 kW.

- 3) The occurrence of wind does not influence the time at which maximal load occurs.
- 4) The occurrence of wind may influence the absolute size of maximum load. Any such influence is, however, supposed to be less than 1% at wind velocities of 15-20 m/sec, which means that 2,000 "Gedser mills" would have a load-dependent output value of less than 10%. /17

Because the load-dependent output value of a greater number of mills is quite small -- below 10% -- it seems reasonable to add 10% to the output value of the windmills for the import of power, maximally 30% as far as Elsam is concerned, regardless of the time.

This output value is added to the windmills because for power plants the foreign hook-ups may act as a reserve for the windmills, and the other way around. Thus the output value of the windmills does not result in savings in the transmission network -- the power must also be transmitted during periods with no wind --, but only in savings as far as the production system is concerned.

The monetary value of the 10% and 30% output value, respectively, which may be ascribed to the wind power, amounts to about Kr. 100-160 or ca. Kr. 300-500 respectively, per kW of wind power output. These amounts correspond to about 3-5% and 9-14%, respectively, of the specific construction cost of a "Gedser mill," and the energy cost of wind power is therefore reduced by about these percentages (somewhat less, because operating costs remain the same). However, at the same time there is a reduction in the savings on the alternative steam power production -- now the average production and not the marginal production is saved -- and the economic circumstances are therefore about as described in Section 3.4, in which wind power is only considered in its fuel-saving capacity. (In the most advantageous locations, the West coast of Jutland, the economic circumstances are improved about 6% over that given in Section 3.4.)

3.5.1. Wind power supplemented with reserve power

On the basis of the considerations discussed above, the requisite for considering a windmill a viable alternative to a steam power plant is that the windmill be equipped with some reserve power.

However, it would only be profitable to supplement wind power with reserve power if the construction costs which are saved by putting in the cheaper reserve power are smaller than the

retrospectively discounted operating costs for such reserve power.

If gas turbines are used as the spare power system, operating costs would be smaller than the construction savings at an annual production time for the gas turbine of up to 50-100 times (interest rate 12-16%, write-off time 20 years) for the alternative of an intermediate load system, and up to 200-400 hours for the alternative of a basic load system. However, it is thought that the gas turbines would have a greater production time, and it is therefore not advantageous to supply the wind power with reserve power. /18

3.6. Energy-economic comparison between wind power and steam power plants

The consumption of scarce fossil fuels is calculated for both wind power and steam power plants.

The energy consumption of a "Gedser mill" may, on the basis of Ref. 4 in the Bibliography, may be calculated at about 60 tons of oil equivalent, of which about half is used for the tower itself.

In figuring the energy value of the steam power saved, we may disregard the energy value of the steam power and transmission systems. (The energy value of the steam power system thus amounts to roughly 80 tons of oil equivalent per MW power, or about 5-10 tons of oil equivalent for an energy production which corresponds to that of the windmill.)

The following considerations are therefore valid regardless of the possible output value of the wind power.

A windmill with an annual production W will, in the course of the 20-year write-off period, save fuel with an energy value of:

$$\frac{20 \cdot W}{1-p} \cdot q$$

For a "Gedser mill" this amounts to a fuel savings of 1,700-3,000 tons of oil equivalent. (The lower figure is for a mill located at Tune, the higher figure is for the location at Torsminde.)

In establishing a windmill it is thus possible to save about 1,600-3,000 tons of oil equivalent, or about 25-50 times as much fossil fuel as is consumed.

4. Recent investigations abroad

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Within the last couple of years, new investigations into the exploitation of wind power in the production of electricity have been started in a number of places around the world, first and foremost in the U.S., but also in Canada, Sweden, (Vattenfall, et al), France and other places (see Bibliographic references Nos. 5, 6, 7 and 8).

The following is a brief description of the investigation at Vattenfall, which as far as is known is the only new technical-economic investigation which has been brought to a preliminary conclusion, and of the NSF and NASA projects in the U.S. Further, a brief summary will be given of an international conference in Stockholm in August of 1974 concerning the exploitation of wind power.

4.1. The investigations at Vattenfall.

In Sweden, Vattenfall has calculated a windmill (Ref 6 in the Bibliography) with the following data:

Height of tower: 60 m.

Diameter of propeller: 57 m ($\approx 2550 \text{ m}^2$ wing span area)

Directly coupled synchronous generator, 2,000 kW, 1, 6 kV, 200 poles, 30 rev/min (outside diameter ca. 7 m, weight ca. 50 tons).

The mill yields 2,000 kW at a wind velocity of 15 m/sec.

The angle of the blade is regulated according to the velocity of the wind.

Annual yield 3,400-5,100 MWh, mean value 4,100 MWh

($\sim 1,600 \text{ kWh/m}^2$ per year and $\sim 2050 \text{ kWh/kW}$)

Transformation up to the 70 kW net is joint for a "wind power block".

In serial production, the cost of a single mill is calculated at between 6 and 8 million Swedish Kroners (3-4,000 Skr/kW) corresponding to (with Swedish interest rates) 15-20 Søre/kW as opposed to ca. 5 Søre/kWh for energy produced by nuclear power.

The Vattenfall investigation is interesting among other things because of the synchronous generator which is directly coupled to the propeller, and which has 200 poles. This form of coupling is used to avoid the gear, which simply from the construction point of view offers problems because of the great demands for reliability, and which also may cause noise problems.

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On the basis of the economic results obtained from the investigations, Wattenfall has for the time being stopped its investigations of the use of wind power for the "commercial"

production of electricity. Together with Chalmers Technical College Wattenfall has started experiments using wind power for the production of heat in private houses.

4.2. The projects at NSF and NASA

In the U.S., as part of the National Science Foundation's Solar Energy Program, a two-year project has been started, in the course of which a 100 kW experimental windmill is to be erected. [Ref. 7].

The purpose of the project is [Ref. 7] "to determine the performance, operating and economic characteristics of such systems for the future generation of commercial electric power and to identify technical problems and areas where research and advanced concepts could increase performance and decrease costs", and the 100 kW mill is considered a step towards future windmills of 1-2 MW.

Preliminary data for the 100 kW mill, which is to be built by NASA's Lewis Research Center in Cleveland, Ohio, are:

Height of tower: 38 m

Diameter of propeller: 38 m ($\sim 1140 \text{ m}^2$ wing span area)

The propeller is located on the lee side of the tower.

100 kW generator, 4 poles, 1,800 rev/min

The conversion ratio for the transmission system between propeller hub and generator is 1:45 (at 18 mph).

The mill starts at 7 mph ($\sim 3.1 \text{ m/sec}$) and yields 100 kW at 18 mph ($\sim 8.0 \text{ m/sec}$).

The angle of the blades is adjusted according to the velocity of the wind. At velocities above 60 mph ($\sim 27 \text{ m/sec}$) the mill is stopped.

Anticipated annual yield 180,000 kWh ($\sim 160 \text{ kWh/m}^2$ per year and $\sim 1,800 \text{ kWh/kW}$).

Compared to the Gedser mill, the anticipated annual yield is thus rather low; about 160 kWh/m^2 compared with the approximately 900 kWh/m^2 from the Gedser mill. This difference is in part due to the more favorable wind conditions at Gedser, and in part to the fact that the Gedser mill was designed to exploit greater wind velocities, so that it would not even start at wind speeds below 5 m/sec . /21

4.3. The Stockholm conference on Wind power systems.

During the days of August 29-30, 1974, a conference was held in Stockholm concerning "Advanced Wind Energy Systems".

About 65 people from nine countries participated in the conference.

Below are some impressions gathered at the conference.

At the conference only one recent, full-scale windmill was discussed, namely the 70 kW pre-prototype at Sild, built by the Swiss firm NOAH. This windmill has two sets of 5-bladed propellers, turning in opposite directions from each other. The propellers are directly connected to stator and rotor, respectively, on the mill's synchronous generator. By this means the gear is avoided, although the synchronous generator has "only" 42 poles (the number of poles should be twice that, if the stator stood still).

The cost of the Sild mill was said to be about Sfr. 2,000 per kW (about 4,100 Kr/kW), or about 20% more than that which has been calculated for a newly constructed Gedser mill. There is as yet no information regarding the energy production of the new Swiss mill.

Swedish representatives presented the project which has been described in Section 4.1.

Representatives from Canada, the U.S., Holland and Denmark (F. L. Smidth) discussed investigations concerning windmills with a vertical axle (of the Darrieus type). A Canadian experimental mill of the Darrieus type -- with an energy output of 0.9 kW -- is shown on Figure 10. Mills with a vertical axle have the advantage that the heaviest parts -- generator and gearing -- rest on the ground, which means that they are in a safe place and that a lot of money is saved on the tower. In addition, such a mill can instantly exploit wind coming from varying directions. On the other hand, the tower is subjected to strain from the wings -- quite the opposite of what is true for mills with a horizontal axle -- and this stress must be compensated for, for instance by means of guy wires fastened to the top of the mill.

No actual projects or more detailed economic calculations were presented concerning the Darrieus mill. A Danish representative (F. L. Smidth) discussed an outlined 1.2 MW mill (total height 135 m) equipped with six Darrieus rotors. Construction costs for this were estimated at 3,000 Kr/kW, with an annual energy production of 3,000 kWh/kW. If these estimates are correct, the result would be an energy price which is about 20% lower than that which was calculated on the basis of the Gedser mill project. Prices on that same level were also quoted by the Boeing Vertol Company, which has sketched a windmill with a horizontal axle and a single-bladed propeller. /22

English representatives discussed a project involving a 50 kW windmill, intended to supply a fairly large household,

primarily with heat and secondarily with electricity. The heat is produced in a container by a sort of churn, to which energy is mechanically transferred from the propeller. The mill's propeller is not tied to a certain number of revolutions, but will always run optimally in relation to the wind speed. The energy is stored in two heat storage units, one high-temperature unit (270°C, with heat to be used for such things as food preparation) and one low-temperature unit (80°C, to be used for heating, etc, with a capacity of 2,100 kWh).

Canadian representatives presented the results of calculations concerning the influence which windmills will have on each other if they are placed very close together. So far it has been assumed that windmills could be placed at a distance from each other of about 7-10 propeller diameters, without any undue effect on energy production. The Canadian calculations (Fig. 11) suggest, however, that there is a considerable reduction in energy if the proportion between propeller area and surface area exceeds about 10^{-3} , corresponding to a distance of one mill from any other mill of fewer than 30 propeller diameters. If all of Denmark were to be covered with windmills placed at this distance from each other, the maximum obtainable propeller area would be 45 km², corresponding to an annual energy production of 2-3 times the present consumption of electricity.

5. Smaller windmills

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When smaller windmills are involved, which are not hooked up to a common electrical supply network, the mechanical energy is either used directly -- especially for pumping water, such as formerly was common on Danish farms and in the marshlands, -- or it is converted to electrical energy in the form of direct current. Conversion to direct current has in recent years been used especially in isolated places, such as relay stations in the telecommunications net, weather stations and lighthouses.

If the energy is converted to direct current instead of to alternate current, the propeller is not forced to run at a certain number of revolutions, with the result that its total energy output may be somewhat better than that of the alternate current mill.

Windmills of the direct current variety are today produced in several places around the world (in Europe by such firms as, for instance, the Swiss firm Elektro and the French Aerowatt, which since 1970 has sold about 200 mills). The mills' maximum power output ranges from about 20 watt up to about 10 kW. They are normally built to start at relatively low wind speeds, 2-5 m/sec, with their maximum power output being reached already by about 5-10 m/sec, which means that the amount of time the mill is in use is somewhat greater than is true of, for instance, the Gedser mill (against a larger wing span area/energy production ratio).

The smallest windmills -- with an energy effect of up to ca. 500 watt -- are often built with a vertical axle, while the larger mills are built with a horizontal axle.

The cost of serially produced mills of a few kW's size is quoted (among other places, in Ref. 5) as about 2-3,000 Kr/kW exclusive of transportation and installation, but higher prices -- up to 10,000 Kr/kW -- have also been quoted.

The 2 kW direct current windmill (rotor diameter 12 feet) referred to in Ref. 5 will here be discussed as an example of a smaller windmill. This mill supplies an isolated family with the electricity it needs (1,500 kWh/year). Nineteen accumulators with a total of 15 kWh are used to store energy for use in windless periods. The family's consumption of electricity is geared to direct use of the direct current energy, but television and radio are supplied by means of a converter. Total cost for such a system is said to be \$2,800.

As mentioned earlier, there are considerable variations in the prices quoted for mills in the written material used, and the mills' effectiveness curves are not given, so it is difficult to estimate the cost per kWh produced by a direct current mill. However, on the basis of the information available it seems reasonable to explore more closely the technological and economic ramifications (along the lines of the joint investigations by Vattenfall and Chalmers Technical College) of the smaller windmills' ability to cover the energy consumption in non-urban areas, especially that part of the energy which is used for heating houses, because in this case the energy may be stored in larger water tanks -- a water tank of ca. 40 m³ would be sufficient to heat a single-family dwelling for a month under normal conditions). /24

6. Environmental issues

The following will deal with the environmental disadvantages resulting from the production of electricity by means of wind power. The chief of these disadvantages is noise, followed by visual pollution and the need for large amounts of space.

The environmental advantages of wind power production -- consisting of the limitation of the disadvantages incurred by steam power production -- will not be discussed further at this time, because Ref. 2 gives an account of these circumstances, dealing with such issues as air pollution, thermal wastes, water pollution, safety, refuse, etc.

6.1. Noise

The noise occasioned by a windmill consists of a low-pitched humming produced by the gearing as well as a rushing sound due to the partial vacuum on the backside of the wings.

If necessary, it is possible to reduce the noise by means of adjustments in the mill's design. In the case of the Gedser mill, however, this did not seem to be necessary, because the amount of noise at the foot of the tower was moderate and completely negligible at a distance of 100 meters from the tower. French experiences show, moreover, that the rushing sound produced by the wings does not constitute a problem at peripheral speeds below 100 m/sec. (Peripheral speed at the Gedser mill was 38 m/sec).

6.2. Visual pollution

The greatest environmental problem in connection with the exploitation of wind power is how to fit the mills into the landscape. In order to obtain maximum production, the mills should preferably be located on top of hills, ridges, etc, in other words, in places where they can be seen from far away, and they should preferably be along the coast. /25

If one assumes that 10% of the present domestic consumption of electricity is to be met by "Gedser mills" placed along the West coast, 3,100 mills will be built, about 100 m apart, all along the free and open part of the coast that faces west (or in the ocean a short distance from the coast). Such placement of the windmills would make it impossible to preserve the visual value of the landscape. And, as the Canadian investigations suggest, it is desirable to place the windmills much farther apart in order actually to obtain the projected energy production. One would therefore have to allow for spreading out the windmills over the better part of the country (for 3,100 mills the average distance between two neighboring mills would be about 4 km), which in turn would mean that one would have to use locations which are less desirable from the point of view of production.

In connection with the visual aspect of the problem, the shape of the mill plays an important part, and a great deal of consideration should be given to this fact in designing the mills. Another matter of consequence is the 10 kV hook-up, which probably will have to be done by cable, so that aerial wires are avoided.

6.3. The need for space

The space requirements of the "Gedser mills" will -- if the country's entire electricity consumption were to be covered by wind power -- be on the order of 60 km² (1,200 m² per mill) as opposed to 1-2 km² for conventional power plants. However, about 80-90% of those 60 km² could be cultivated (such as was the case at the Gedser mill), so the actual amount of space used would only be about double that used for conventional power plants.

7. Conclusion

This inquiry concentrates on the question of using wind power for the production of electrical power. Such electrical power produced by means of the wind's energy would supposedly be funnelled directly into the existing supply network as a supplement to electrical power produced by means of fossil fuels. /26

On the basis of the results obtained from the Wind Power Committee's experimental mill at Gedser, the construction cost of larger windmills today would be estimated at around 3,500 Kr/kW.

The annual production of energy is estimated to be between 2,700 kWh/kW for a windmill placed in the most favorable spot on the West coast of Jutland and 1,600 kWh/kW for a mill located in the most favorable spot in the interior.

It is, of course, debatable whether it is possible to draw general conclusions regarding the economics of wind power on the basis of 200 kW mills -- might not larger mills be more economical? The largest mills outlined at this time are windmills with a capacity 5-10 times that of the Gedser mill. However, investigations in other countries suggest that one may not be able to count on a significantly improved production from the economic point of view with the larger mills, either.

Naturally, any production cost calculated for wind power on the basis of the figures given above would be very much dependent on such conditions as the length of the write-off period, the interest rate used in the calculations, and the rate of inflation.

If, for instance, a write-off period of 20 years is assumed, along with an interest rate of 16% per year and an inflation rate of 10% per year (which, as far as wind power plants is concerned would only affect maintenance costs), the production cost for wind power electricity from an optimally located mill would be 25 øre/kWh the first year, increasing to 42 øre/kWh towards the end of the 20-year period. Corresponding figures for optimal locations in the interior would be 40 øre/kWh and 57 øre/kWh respectively.

Every kWh of electrical energy produced by means of wind power constitutes a saving in expenses for fossil fuels used in other forms of electricity production. At a 1974 fuel cost of 30 Kr/Gcal, increasing by the generally assumed inflation factor of 10% per year, this saving is estimated to be 8.5 øre/kWh during the initial year, going as high as 58 øre/kWh towards the end of the 20-year period.

Retrospective discounting of all expenses and savings over a 20-year period shows that the expenses connected with the /27

wind powered production is at least 60% greater than the savings on fuel costs.

The assumptions made concerning future fuel prices are, of course, subject to a great deal of uncertainty. Right now, the price of heavy fuel oil is in the neighborhood of 40 Kr/Gcal, while the cost of coal is closer to 30 Kr/Gcal. On the other hand, it is surely overly pessimistic to assume that the fuel costs for the power plants will go up at the same rate as the general inflation. Taken all together, it seems that the savings on fuel which have been calculated to take place by substituting electricity obtained from wind power, estimated over a 20-year period, might very well be smaller than estimated.

Due to the way in which the strength of the wind is distributed throughout the year, it is not possible for windmills to replace other ways of expanding the electrical production apparatus; it is doubtful that the general value of their contribution to the electrical system may be set at more than 10% of their total capacity.

Therefore, the construction of windmills represents an additional investment which, by using wind energy on a larger scale, would have a noticeable effect on our society's already scarce capital resources. If, for instance, 10% of the country's present consumption of electricity (corresponding to about 2.5% of our total import of energy) were to be covered by wind energy, an additional investment of at least 2,200 million Kroners would thus be necessary.

As may be seen, it is not possible to obtain a reasonable return on such additional investments if the matter is regarded from the point of view of conventional economics. However, this situation may change, if fuel costs go up even faster than the general rate of inflation, or if new developments were to lead to a drastic reduction in specific construction costs for windmills. As far as the latter point goes, there does not seem to be any great cause for optimism at the present.

Seen over a period of many years, the use of wind power has advantages in the area of foreign currencies. Foreign currency expenditures involved in the construction of a windmill are estimated to be about 20-30% of the total construction costs. On the other hand, there is a saving on foreign currencies which would otherwise be spent on fuels, and from the point of view of foreign currency considerations alone, a windmill would pay for itself in the course of 5-10 years, depending on its locations, etc. To this is added the fact that the country would be somewhat less dependent on fuel deliveries from abroad.

From the point of view of global resources, wind power is, /28
of course, an attractive option. The savings on fossil fuels is
estimated at about 75-150 tons of oil equivalent per Gedser
mill per year.

From the environmental point of view there are both advantages
and disadvantages connected with the exploitation of wind power.
On the plus side are such things as the reduction in chemical
and thermal emissions from the power plants. On the minus side
the impact on the landscape is far and away the most important
consideration.

Appendix A

The Gedser mill

On the basis of Ref. 1 a brief summary will be given of the /A data concerning the Gedser mill.

The Gedser mill's wings, its electrical equipment and transformer station, and its hook-up to the regular power network, have been executed by SEAS. The engine hut and its mounting and assembly were done by Aarhus Maskinfabrik. The tower was planned and calculated by Dr. Tech. B. Højlund Rasmussen, and the tower was built by the contractor firm of Larsen & Nielsen Construction, Inc., Copenhagen.

A.1. The tower

The construction of the mill is shown in Fig. 2, where it becomes apparent how the wings and their guy wires, as well as the engine hut, are placed on the tower. The tower consists of a vertical tube (1) made of stressed concrete, while the supporting ribs (2) and foundation (3) are made of regular reinforced concrete. (4) is a cylinder gauge, placed between the engine hut and the tower in order to register the wind's impact on the mill.

(5) is a service platform, accessible by an interior as well as an exterior ladder (6).

The transformer house (7) is built next to the tower.

A.2. The wings

By means of a gear the wings of the Gedser mill were coupled to an asynchronous alternate current generator, which in turn was connected to the supply net. Therefore the wing's number of revolutions was determined by the network frequency and the coupling of the gearing and varied only as much as the slip of the generator, about 1% maximum.

In order to determine the wing's number of revolutions and peripheral speed the SEAS performed tests in a makeshift wind tunnel with various wing profiles, and they gathered measurements of wind energy on South Shetland. These tests and inquiries resulted in a choice of wing diameter of 24 m and a revolution number of 30 rev/min, corresponding to a peripheral speed of 38 m/sec. With such data the wings were most effective at a wind velocity of 8 m/sec (Fig. 3, Curve 1), which -- by locating the mill in South Shetland -- should result in optimum production.

Figure 3 shows the resulting curve of the Gedser mill, in Curve 2 (exclusive of some losses?). Due to the stalling phenomenon (the partial vacuum on the back side, which reached a "saturation point") the curve levels out at wind speeds above 15 m/sec, which means that the danger of overload in case of a storm is avoided.

/A-2

The wings, shown in Figure 4, were constructed with a view to the feasibility of actually building them. The wings consisted of a carrying beam (4) consisting of steel plates and flat iron bars welded together. A system of wooden ribs was fastened to the flat bars, and 1 mm thick light alloy metal plates were fastened to the ribs.

At the tip of each wing was a brake flap (1), which during normal operation formed an integral part of the wing. If it became necessary to stop the mill, however, a hydraulic servomotor would automatically twist the brake flap 60° out from the rest of the wing surface, thus bringing the mill to a standstill.

The wing system of the Gedser mill was suspended at a tilt of 10° in relation to the vertical plane. This was done to gain sufficient room between the wings and the area in which the tower interfered with the wind.

A.3. The engine hut

Figure 5 shows the construction of the engine hut. The engine hut holds the generator (16) and the propeller hub (2) as well as the oiled roller chain gearing (9, 10, 11, 12, 13 and 14) which transmitted the energy from propeller hub to generator axle (15).

The engine hut was mounted to a bottom frame (22), which in turn was fastened to a responsive ring which would keep turning into the wind (23).

On top of the engine hut a wind vane was placed (24), which served to keep the wings into the wind, as it was connected with a motor which would automatically turn the responsive ring whenever needed (at a speed corresponding to one revolution per 15 minutes).

A hole in the bottom of the engine hut allowed for passage of the wires to the transformer as well as of the control wires. Both sets of wires were contained in a freely suspended rubber tube, which could suffer ten revolutions in either direction without being damaged.

A.4. Electrical equipment

In addition to the generator and transformer, which have been described above; the electrical equipment consisted of the

/A-3

equipment necessary for automatic starting and operation of the mill, as well as extensive safety equipment, so that it was possible for the Gedser mill to operate completely automatically.

A.5. Measurements

In connection with the experimental program at the Gedser mill, an extensive program of measurements was carried out. Not only the production of the mill was measured, but also the effect of the wind on the mill as well as the wind's power at Gedser and two other locations in the country.

Annual production at the mill in 1960 and 1961 was measured at 353,000 kWh and 339,020 kWh. On the basis of actual operating time -- allowances had to be made for repairs -- and meteorological conditions, normal annual production was estimated at about 400,000 kWh.

The effects of the wind on the Gedser mill were measured by means of the cylinder gauge (26, Fig. 5) located between the engine hut and the tower. The measurements were made with strain gauges, which registered both static and dynamic effects.

These measurements showed that the mill construction was not subject to strain beyond that allowed for, with an especially large safety margin for axial stresses.

The wind measurements were made by means of power distribution gauges, which reacted to gusts of wind and changing wind directions in the same manner as the Gedser mill itself. The measurements were made at the Gedser mill at heights of 25 m and 50 m above the ground. In addition to the measurements taken at Gedser, which was considered a close-to-optimal location in Denmark from the point of view of maximum energy, wind measurements were taken at a height of 25 m at Torsminde, a location which was considered representative of the best that might be obtained from a station in the interior of Denmark.

The wind measurements showed that the probable annual average outputs at a height of 25 m are:

$$\text{Gedser} \quad 42 \frac{\text{kp}}{\text{m}^2} \frac{\text{m}}{\text{s}} = 410 \text{ W/m}^2 = 3,600 \text{ kWh/m}^2 \text{ per year}$$

$$\begin{array}{llllll} \text{Torsminde} & 49 & - & = 280 & - & = 4,200 & - & - \\ \text{Tune} & 29 & - & = 285 & - & = 2,500 & - & - \end{array}$$

and that the proportion between the output at a height of 50 m and a height of 25 m at Gedser averages 1.21.

Appendix B

The output value of wind power

This appendix will deal with the output value of wind power /B throughout the entire year, with special attention given to times of maximum load.

B.1. Output value throughout the entire year

Figure 12 shows the cumulative power production for a "Gedser mill" located at Risø. Production is shown both for the year as a whole and for the months of December and January separately. The curves are calculated on the basis of wind power measurements taken at Risø at a height of 23 meters every hour throughout the hour (at average intervals of 15 seconds) during the period February 1, 1958 to December 31, 1967, as well as on Curve 2 in Figure 3, which shows the production of power at the Gedser mill at varying wind speeds.

The curves shown in Figure 12 correspond to a utilization time of about 21% (~ 1,800 h/year) for the period as a whole and about 22% (~ 1,900 h/year) for the months of December and January alone. The utilization time of the Gedser mill was about 23% (2,000 h/year). The difference is due to Gedser's being a more advantageous location than Risø (the difference is, however, somewhat greater than the ca. 2% indicated here, because Curve 2 on Fig. 3 is for figures obtained prior to losses in generator, etc).

As may be seen from Fig. 12, the mill's production is limited to about 60% of the year. Although the circumstances would be more favorable if wind power were to be obtained from more geographically spread-out locations -- at Torsminde, for instance, a "Gedser mill" would be productive for about 70 or 80% of the year, with the production to some extent taking place at times when mills elsewhere in the country were not producing -- there would also in this case be extended periods when no wind-power electricity was produced. Therefore an electrical supply system based completely or primarily on windmills would offer completely unacceptable delivery conditions.

On the basis of the curve in Figure 13, an attempt is made /B-2 at examining the importance of wind-power production on a smaller scale. This curve shows the cumulative frequency of non-interrupted power obtained from steam power (drawn up on the basis of conditions at Samkøringen [= "Joint Operations"], Elsam and KB during the calendar year of 1973). Figure 13 shows that throughout this entire period at least 76% of the total power has been available, but that at no time has more than 95% of the total power been available (including for systematic inspection).

If such a steam power system is supplemented by a wind power plant with a total rated output of 10% of that of the steam power system (i.e. of about 400-500 MW), the total cumulative frequency becomes that shown in Figure 13. The curve is calculated on the basis of a power distribution corresponding to that shown in Figure 12 (for the entire period). The power is assumed to be randomly distributed throughout the year according to the curves in Figs. 12 and 13, and no allowances have been made for breakdowns in the windmills.

It may be seen from Fig. 13 that adding 10% wind power will mean that for 50% of the time there will be at least 2% more power available.

The output value derived from wind power is, however, determined as the difference in secured power with and without the addition of wind power. Secured power is -- provided the power curves in Fig. 13 are normally distributed -- that power which is available 98% of the time (Ref. 8). The increase in power during 98% of the time is about 1%. (Exact determination of this quantity presupposes a vast amount of data for the determination of the cumulative frequency of the non-interrupted power supply).

On the basis of these figures the value of the power derived from those 10% of wind power appears to be about 1%, corresponding to a 200 kW windmill's having an output value of about 20 kW. (Whereas 200 kW power derived from steam power has an output value of about $200 \cdot 0.78 \text{ kW} = 156 \text{ kW}$, because ca. 78% of the power derived from steam is non-interrupted 98% of the time). Even if circumstances from the energy point of view are more favorable elsewhere in the country, for example at Torsminde, the output value of a windmill in such places would not be significantly greater than that described above.

B.2. The importance of foreign hook-ups in determining the output value of wind power. /B-3

At the moment the Danish supply areas Kraftimport [Power import] and Elsam have three electrical connections with foreign countries. These connections are established in part because of the need for reserve power and in part to facilitate the exchange of energy between Denmark and other countries to the extent that it is economically advantageous. The fact that these connections guarantee reserves makes it possible for the power systems in any of the given areas to give less thought to planning for reserve power than otherwise would have been the case.

There is no general rule for how one is to calculate how much reserve power can be based on foreign connections. Such calculations must depend on the type of cooperation involved and the

amount of consideration it is necessary to give to cooperating foreign countries. Kraftimport and Elsam consider these foreign connections somewhat differently, and on the basis of Ref. 9 these two areas will therefore be dealt with separately below.

B.2.1. Kraftimport

The capacity of Kraftimport's Øresund connection to Sweden is determined on the basis of an estimate of how much power Kraftimport may be able to count on as an aid from Sweden in the case of power failure here at home. This capacity is in part limited by the cables' ability to transfer the power, and in part by limitations in the transfer of power through the network connecting the southern part of Sweden with the rest of Sweden. Swedish loads and the amount of installed power in that country also play a part. A reasonable mean figure is based on the assumption that half of the Øresund connection's capacity to transfer power constitutes the amount of power which Kraftimport has at its disposal from abroad.

The value of the Øresund connection's power is included in the calculations made for Kraftimport's necessary expansion program and thus serves to reduce the extent to which Danish power plants have to expand. Because the output value of the foreign connection thus serves as a reserve for the steam power plants, it may not at the same time be considered a reserve for wind power.

Thus, the output value of 10% wind power at Kraftimport's -- uninfluenced by the Øresund connection -- will be about 1%.

Elsam

At Elsam, the output value of its foreign connections is determined by the alteration in secured power resulting from these connections. /B-4

In this connection the hook-up with Germany is of particular interest because this linkage connects the relatively small Elsam area to the much larger area of Central and Southern Europe (representing installed power of 100 times that of Elsam's).

If the German connection is sufficiently developed, the secured power becomes that power which is disposable 50-60% of the time, because the foreign connection and the production and transmission system behind it compensate for the power lacking the rest of the time.

On the basis of Fig. 13, the increase in secured power derived from 10% wind power is set at ca. 2%. Ten percent power derived from wind energy at the most favorable location in the Elsam area -- Torsminde -- will increase secured power by about 3%, and

the maximum output value of wind power, when the foreign connections are taken into consideration, will thus be 3/10 - 30%, corresponding to a 200 kW windmill having a maximum output value of about 60 kW. (As opposed to an output value of about $200 \cdot 0.87 = 174$ kW for a 200 kW steam power unit, because ca. 87% of the power derived from steam is non-interrupted 50-60% of the time).

The above presupposes that the German connection -- for different reasons, such as those connected with energy and stability -- be developed more fully than the reserve needs for steam power demand. Something like that is in the making for 1974 and onward.

Finally, it should be mentioned that the energy which must be supplied when the windmills fail will be more expensive than the alternative steam power energy. This is because the energy first has to be imported from Germany -- which charges relatively high prices for "nonintentional" imports -- and then it has to be produced by Elsam's own units at marginal prices.

B.3. Output value at times of maximum load

/B-5

Maximum load for the electrical power plants occur regularly during certain days in December and January, at certain predictable times of day (see table below). However, the occurrence of wind during these two months is rather randomly distributed, so the force of the wind has no influence on the time maximum loads occur.

Even if the force of the wind is not determinant for the time at which maximum load occurs, it might, however, determine the absolute size of such maximum load; for example, 1 to 2% of maximum load might be dependent on the wind.

In order to shed light on this question, conditions at Bornholm were examined. Bornholm was chosen in part because there the sale of electricity, as well as the size and times of maximum load, are well defined, because there is no exchange with other areas, and in part because wind conditions at any given time may be supposed to be about the same throughout the entire area.

It is true for Bornholm, as for the rest of the country, that maximum load (normally) increases every year at a slightly different rate, as does the annual sale of electricity. The relationship between the sale of electricity and maximum load, utilization time, shows a more even tendency, however -- an increase of about 2% on the average in recent years (but a saturation point naturally occurs after a while).

If maximum load is dependent on the wind, it will influence the amount of utilization time. Thus, if maximum load is somewhat greater one year (1% greater, for example) because of the

wind, utilization time will be somewhat less (ca. 1% less) than what might be expected in accordance with the more even type of development (the wind during maximum load will have no influence on annual sales).

Below is a table which shows, for Bornholm, the times at which maximum load occurs, utilization time (calculated on the basis of gross production) and wind velocities measured by the Dueodde Lighthouse shortly before and shortly after the occurrence of maximum load (but only after maximum load occurred in the period 1973/74). The measurements were taken during the last ten years. /B-6

| Year | Maximum load | Utilization time (gross no. of hours) | Hour of the day | Wind velocities | | | |
|---------|--------------|---------------------------------------|-----------------|-----------------|-----------------|-------|------|
| | | | | m/sec | Hour of the day | m/sec | |
| 1964/65 | 22/12 | 7.40 | 4379 | 6.00 | 1.0 | 9.00 | 1.0 |
| 65/66 | 21/12 | 7.55 | 4549 | 6.00 | 4.5 | 9.00 | 4.5 |
| 66/67 | 20/12 | 7.50 | 4664 | 6.00 | 1.0 | 9.00 | 0.0 |
| 67/68 | 15/12 | 7.45 | 4704 | 6.00 | 15.5 | 9.00 | 15.5 |
| 68/69 | 23/12 | 17.30 | 4812 | 15.00 | 9.5 | 18.00 | 9.5 |
| 69/70 | 23/12 | 17.35 | 4907 | 15.00 | 6.5 | 18.00 | 6.5 |
| 70/71 | 18/1 | 17.25 | 4981 | 15.00 | 12.0 | 18.00 | 12.0 |
| 71/72 | 17/1 | 17.30 | 4915 strikes | 15.00 | 19.0 | 18.00 | 22.5 |
| 72/73 | 15/1 | 17.30 | 5094 | 15.00 | 12.5 | 18.00 | 15.5 |
| 73/74 | 18/10 | 11.20 | 5149 | 15.00 | 4.0 | | |

Utilization time, along with the wind velocities (taken as the velocity shortly before the occurrence of maximum load) has been drawn in, year by year, on Fig. 14.

Examination of Fig. 14 involving the years 1964/65-72/73 (1973/74 is not included in the survey because of abnormalities in the load due to the energy crisis) shows that the force of the wind may have some, but not very much, influence on utilization time (on the order of 10-30 hours, or less than 1%), although the situation in 1964/65 deviates from this tendency. The decrease in utilization time from 1970/71 to 1971/72 is not just due to any influence the wind may have had on maximum load, but mostly to the fact that the consumption of electricity in 1971/72 was influenced by strikes.

The considerations entered into above do not prove or make it seem more likely that the force of the wind has any influence

influence on the size of maximum load. However, they do go to show that if the force of the wind does affect the size of maximum load, this influence would today probably not be greater than 1% at wind speeds of 15-20 m/sec (at which speeds the Gedser mill yielded the maximum amount of power).

One percent of the 1973 maximum load of about 3,500 MW corresponds to the maximum production obtained from about 175 "Gedser mills". By building 2,000 "Gedser mills," for example, as an energy alternative to an intermediate load plant of about 200 MW, each of these mills would thus during maximum load have a load-dependent output value of below 10%.

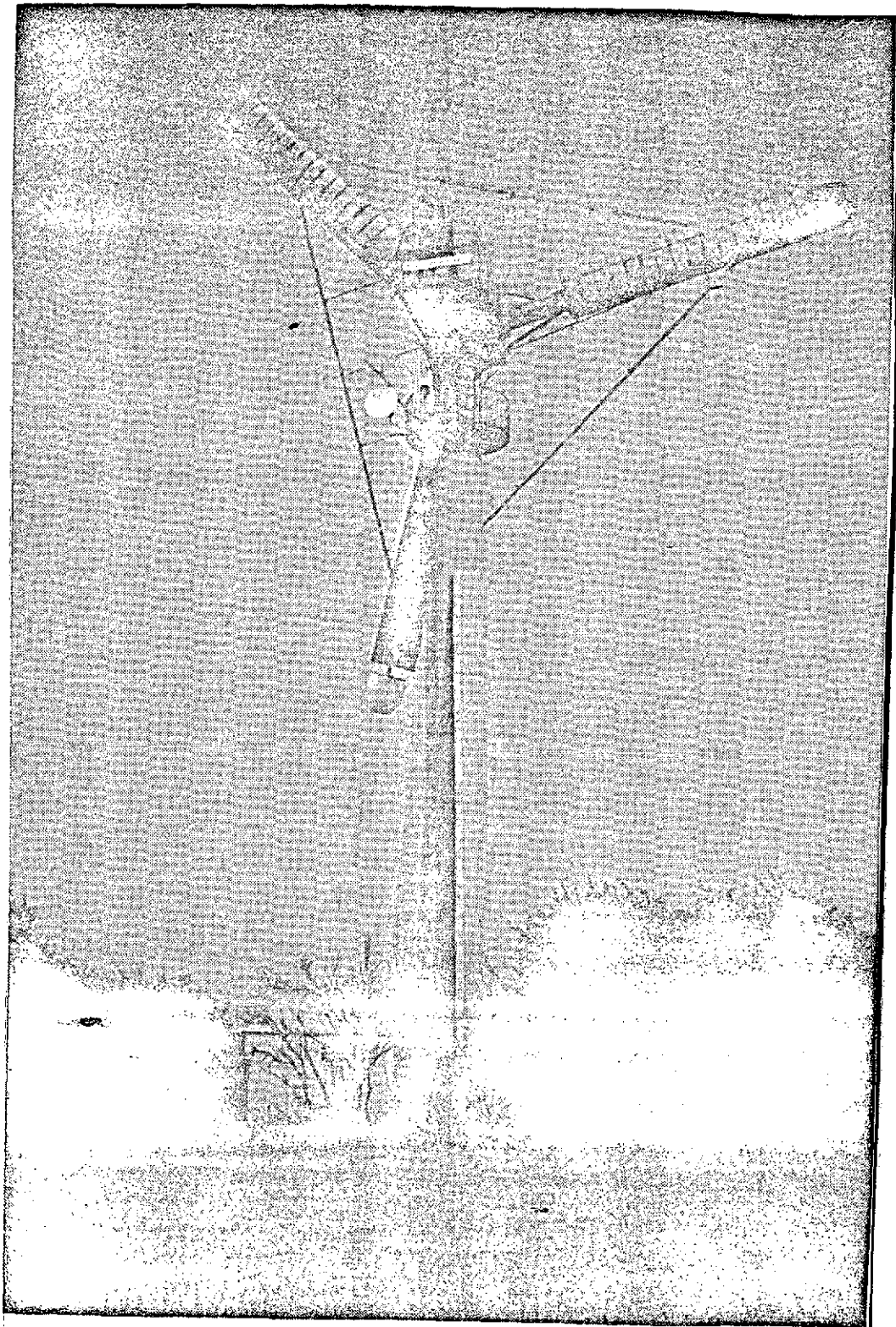
Load dependence on wind in networks serving electrically heated homes /B-7

In Sweden, where 10-15% of homes are electrically heated, it has been noticed (see Ref. 10) that in certain areas there is a relationship between maximum load and wind velocity. In those areas where the relationship is most apparent, the load increases by about 1 o/oo per knot of increased wind speed. This means that the load should be increased by about 2%, if wind speed increased from 5 m/sec to 15 m/sec.

In 1974, about 1.5% of Danish homes are heated electrically. If that number is increased by 10-15% (which might happen in the 1980's), it may be expected that electrical load in this country, at least in certain areas, will be somewhat more dependent on the wind than the case is for Bornholm according to the figures given.

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The Gedser Mill

Figure 1

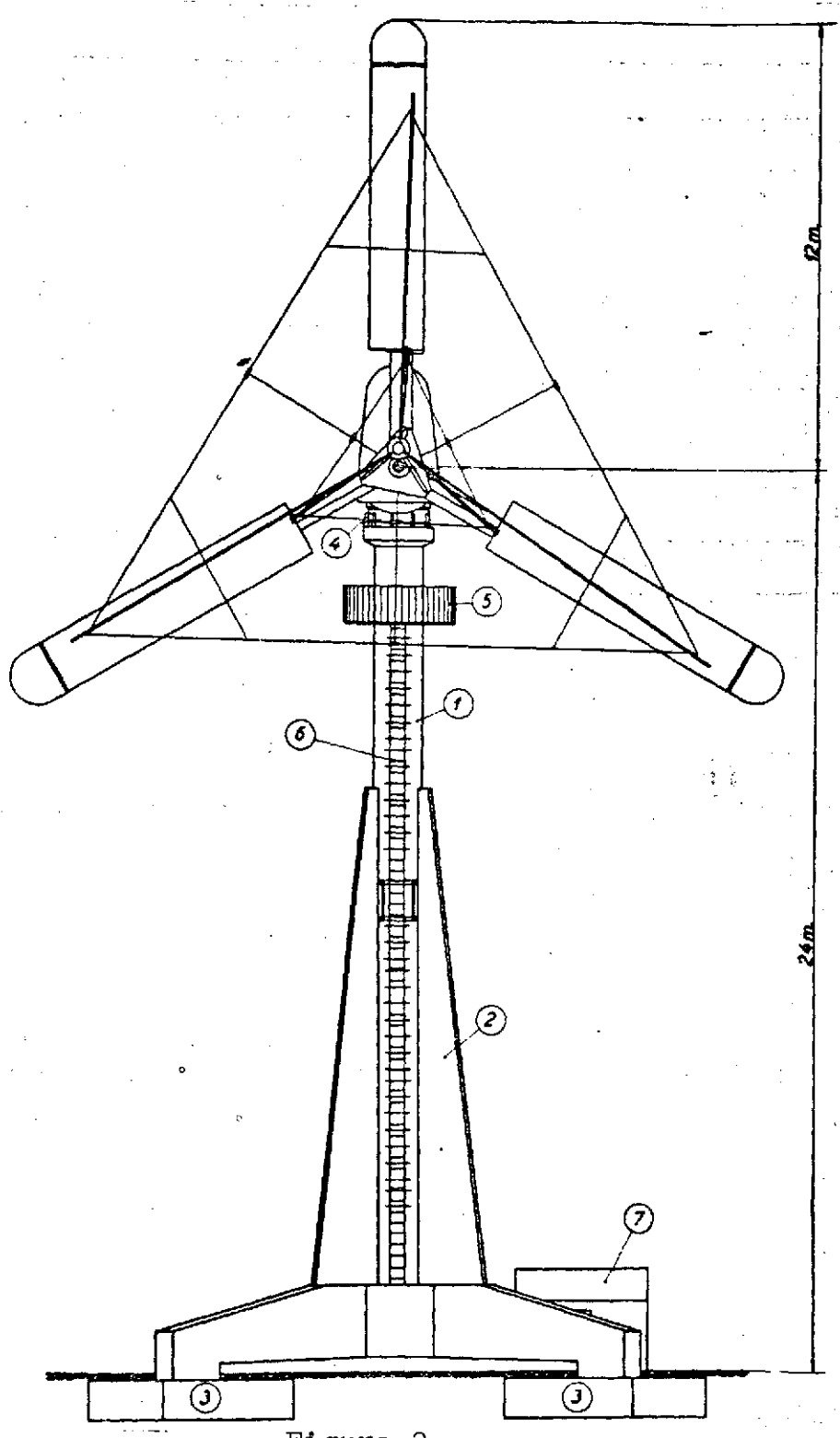


Figure 2

The Gedser Mill. Wing span area 450 m^2 , diameter 24 m -- 200 kW -- wing tip speed 38 m/sec.

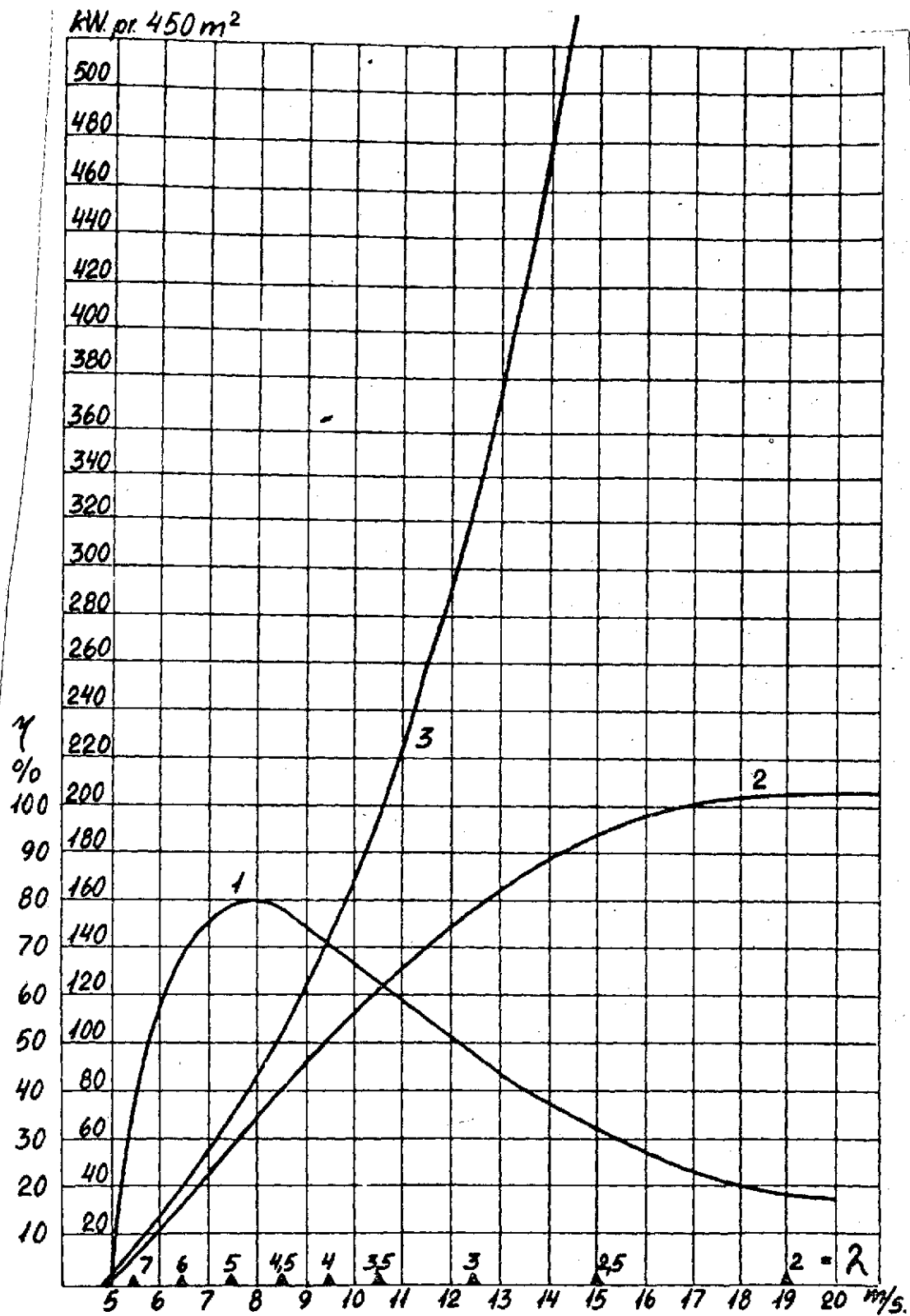


Figure 3

- Curve 1. Effectiveness of the Gedser mill.
- Curve 2. Power derived from the Gedser mill.
- Curve 3. Wind energy calculated according to the formula
 $D^2 \times V^3 \times 0.000285$, with $D = 24$ m.

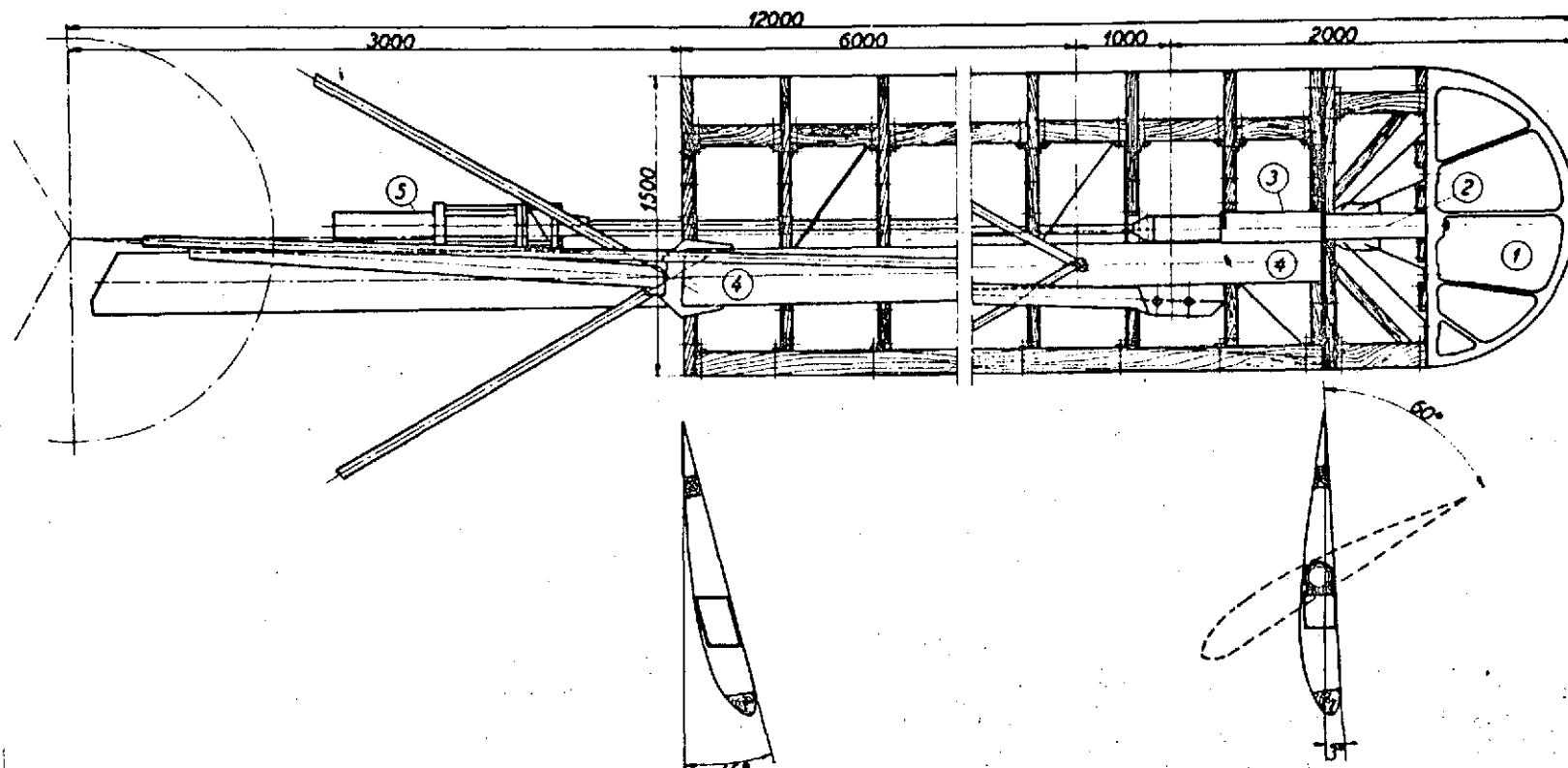


Figure 4

The construction of the GEdser mill's wings

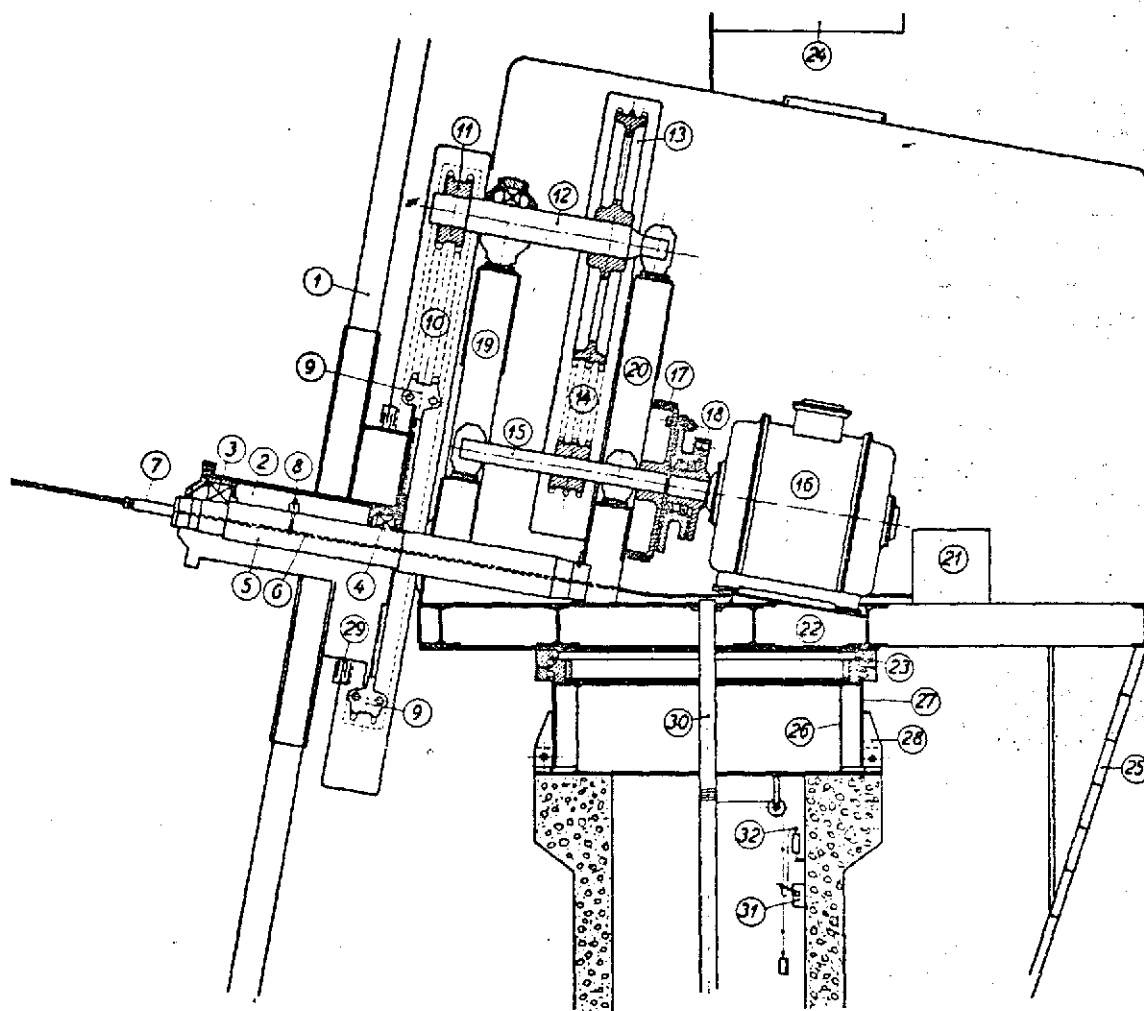


Figure 5
Construction of the engine hut

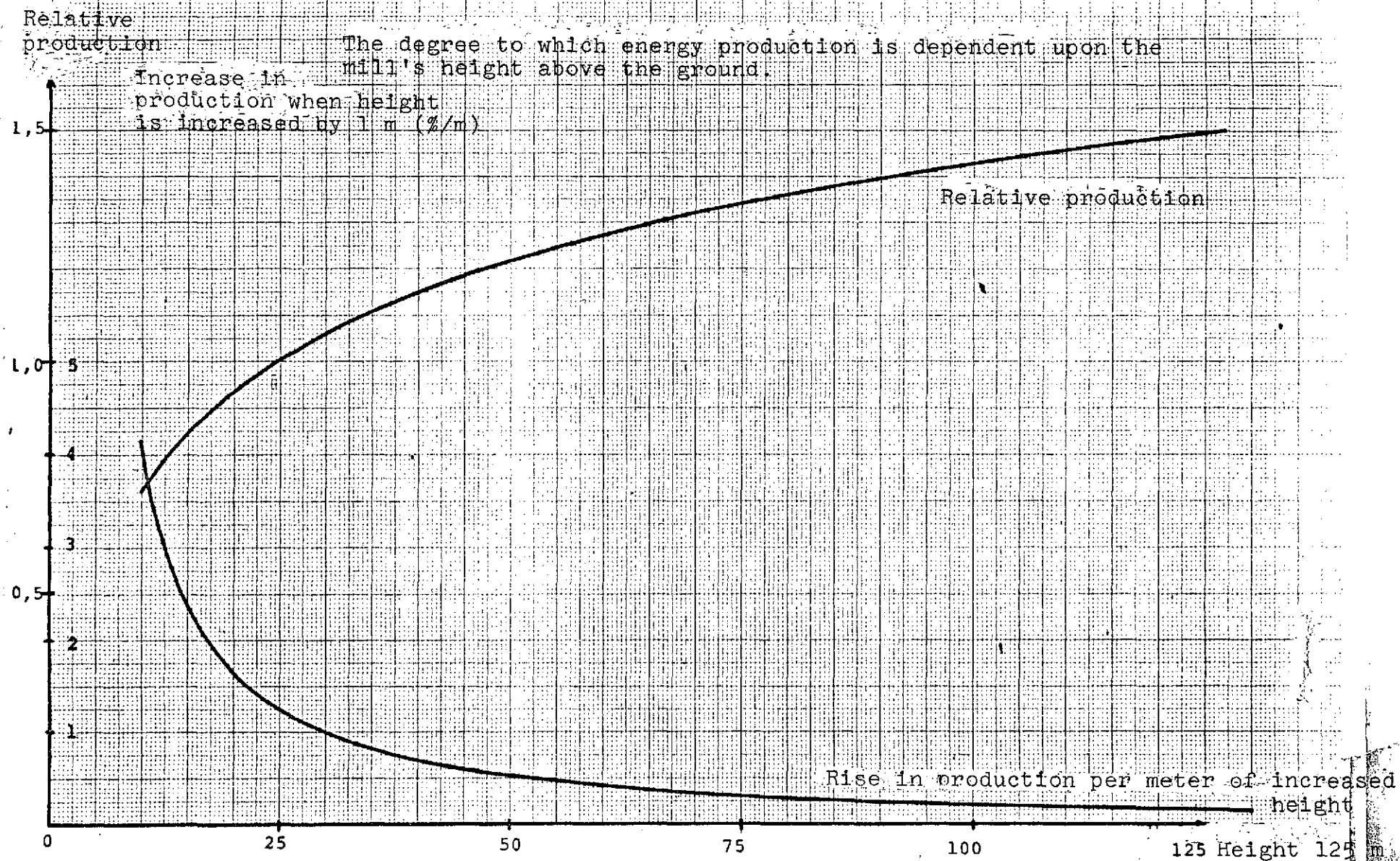


Figure 6

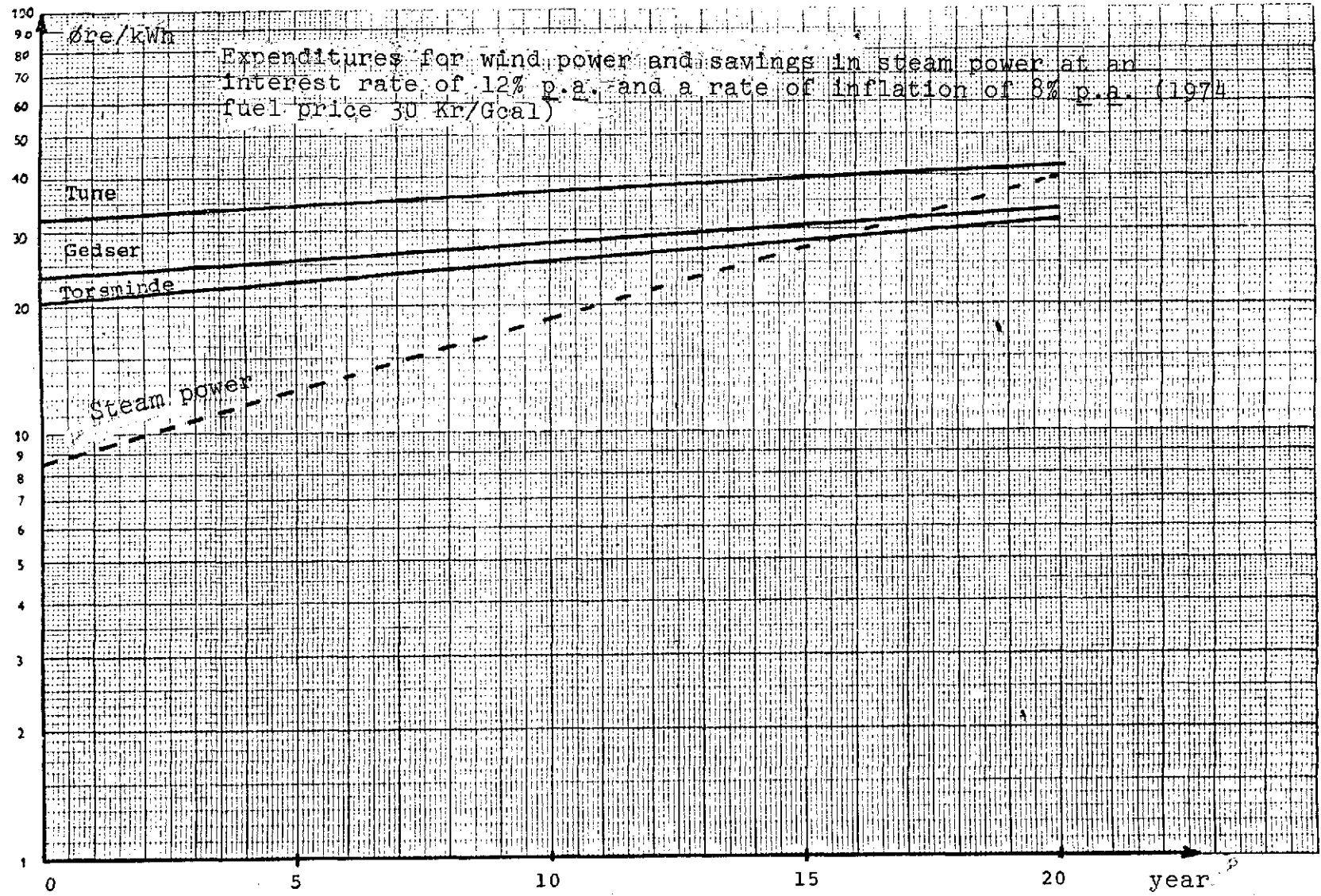


Figure 7

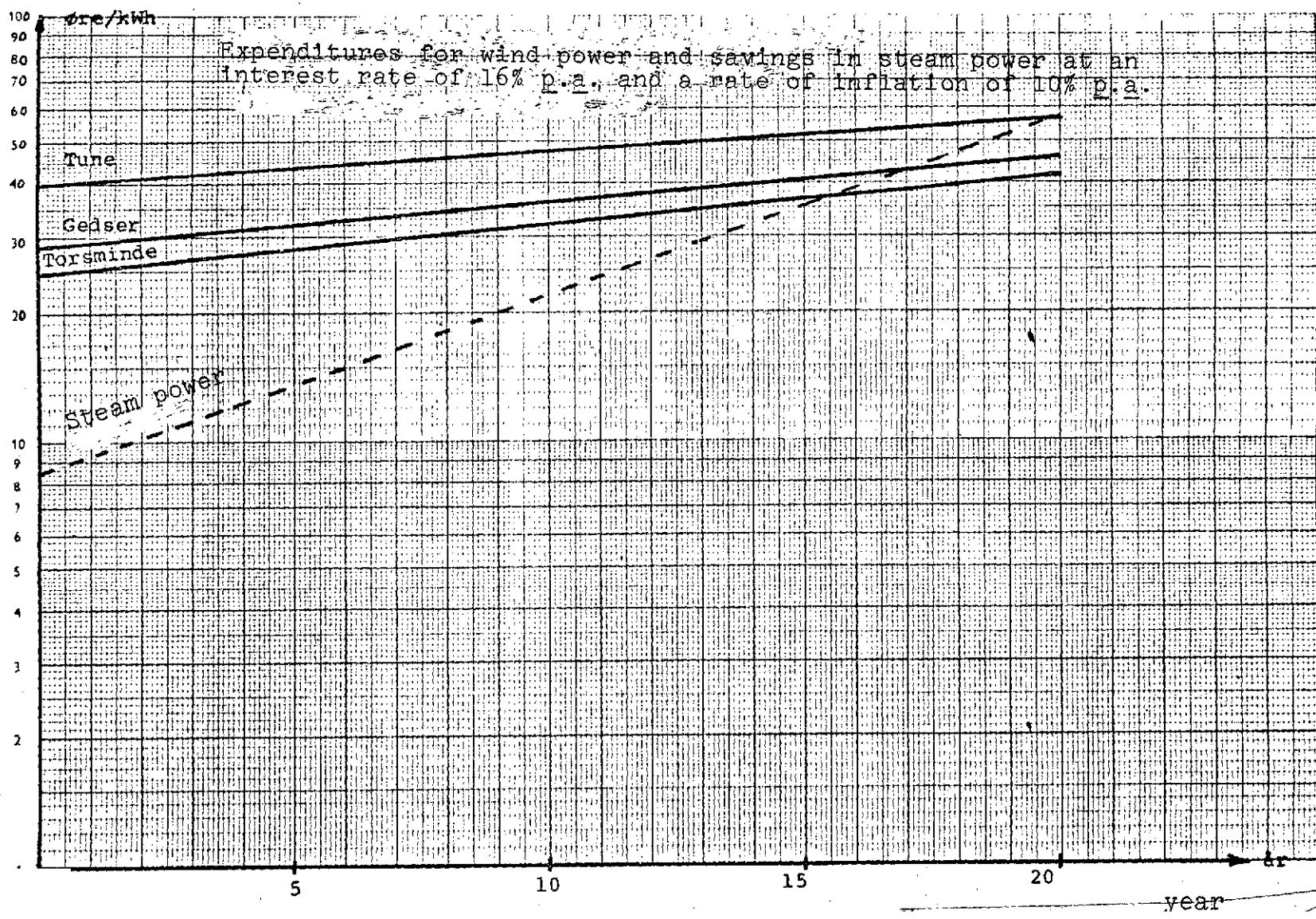


Figure 8

$\frac{A}{E} = f(c)$, equilibrium curve for expenditures
for wind power and savings on steam power
(production).

Below the curve wind power becomes profitable.

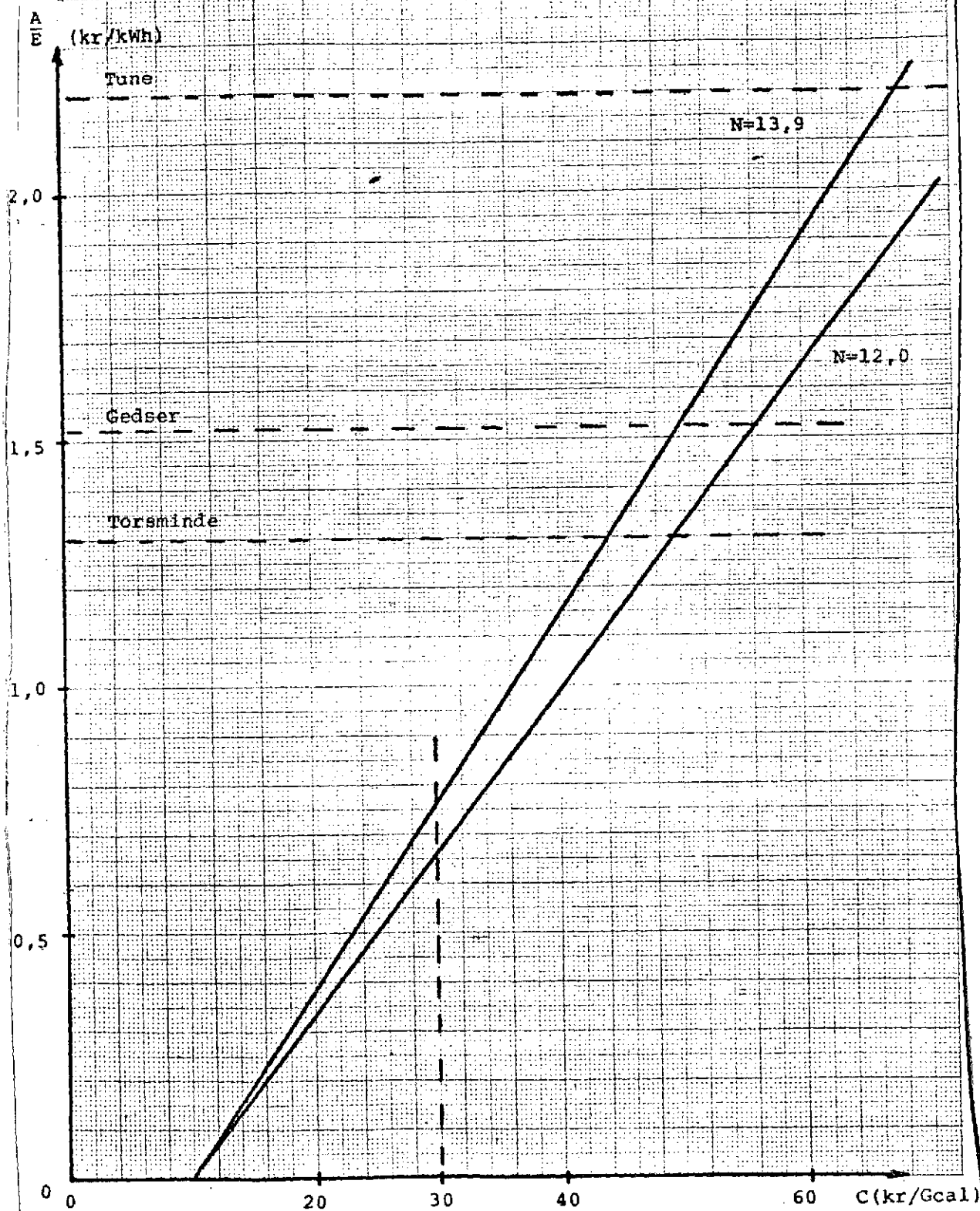


Figure 9

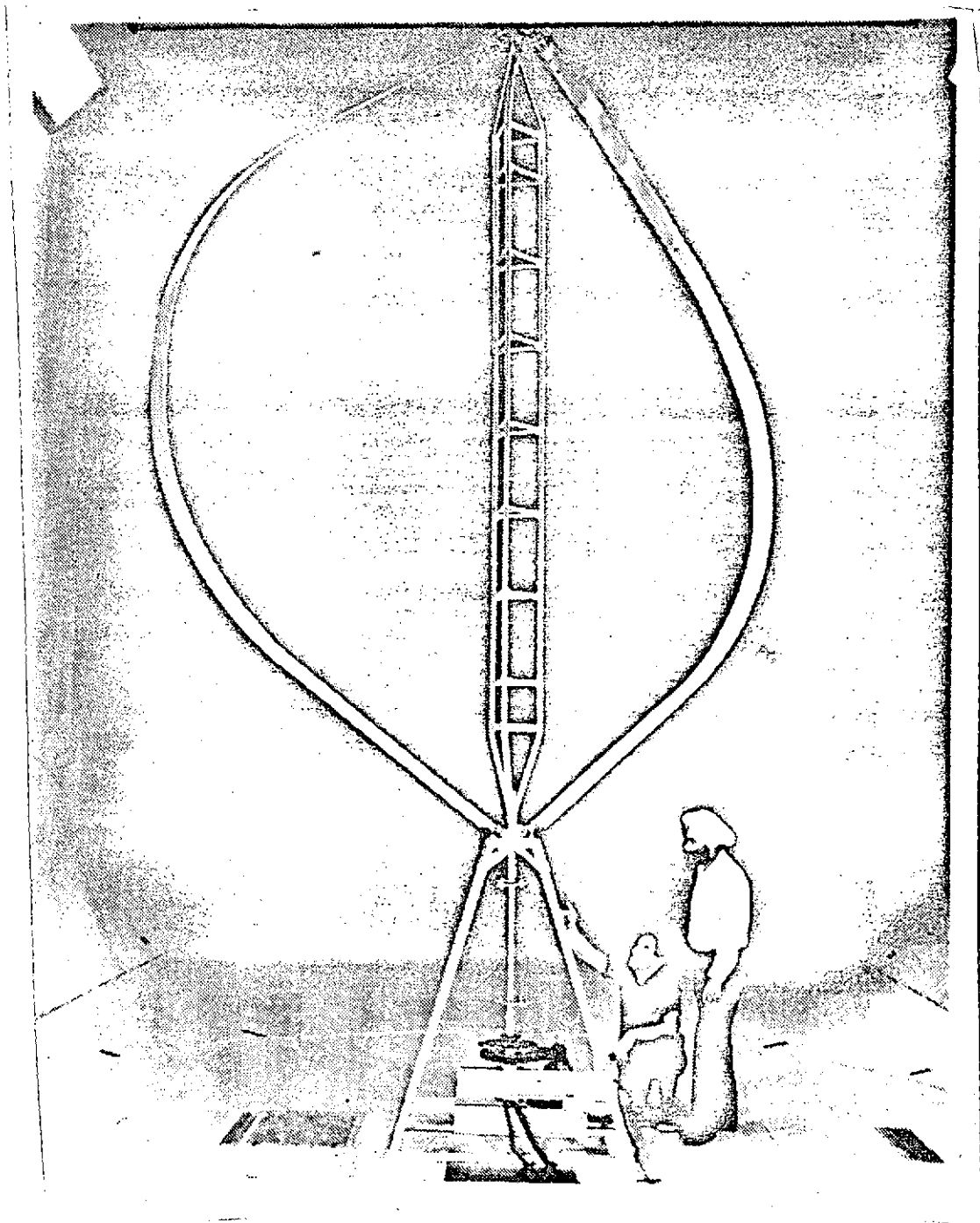
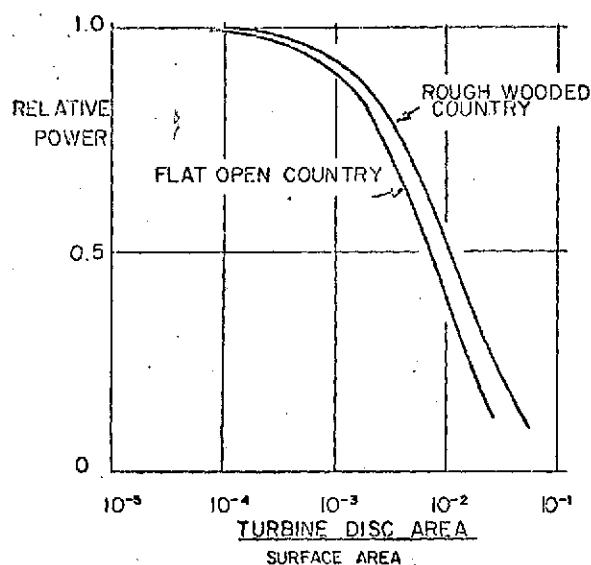
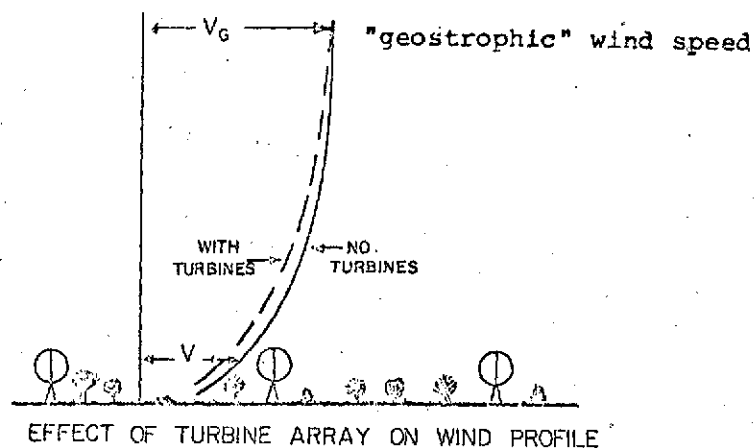


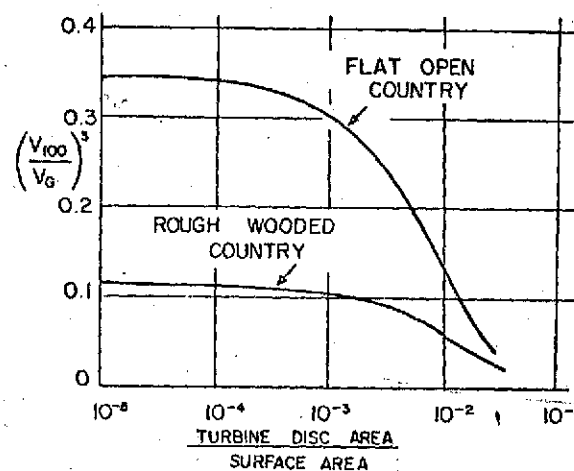
Figure 10

Darrieus mill. Diameter 4.5 m. At a wind velocity of about 6.5 m/sec, the mill produces 0.9 kW.

Figure 11



RELATIVE TURBINE POWER AT 100 FT.
(CONSTANT INITIAL VELOCITY AT 100 FT.)



RELATIVE TURBINE POWER AT 100 FT.
(CONSTANT GRADIENT WIND VELOCITY)

How windmills influence each other

-48-

Cumulative power production of a "Gedser mill" at Risø,
calculated on the basis of wind measurements during the
period Feb. 1, 1958-Dec. 31, 1967.

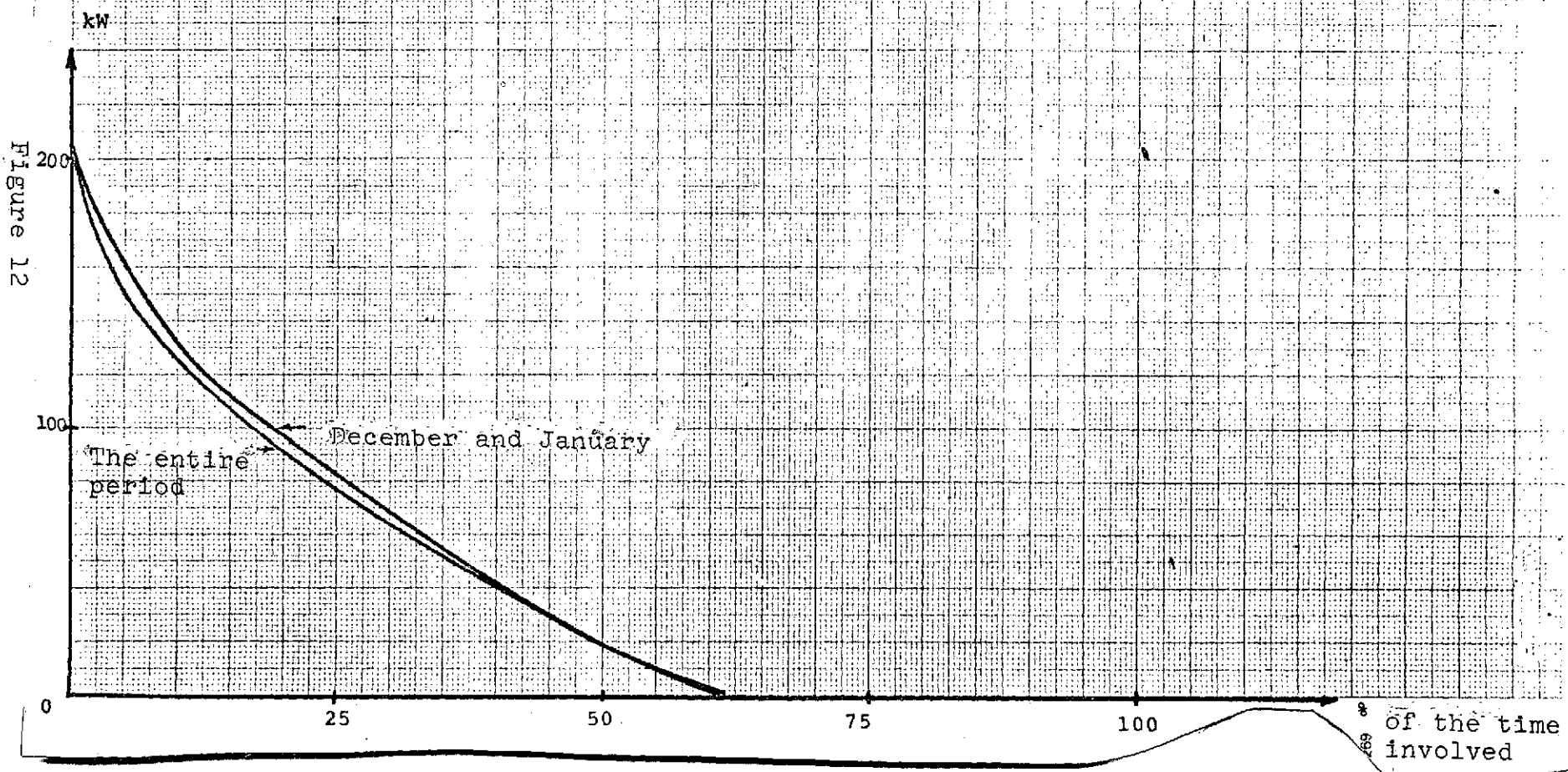
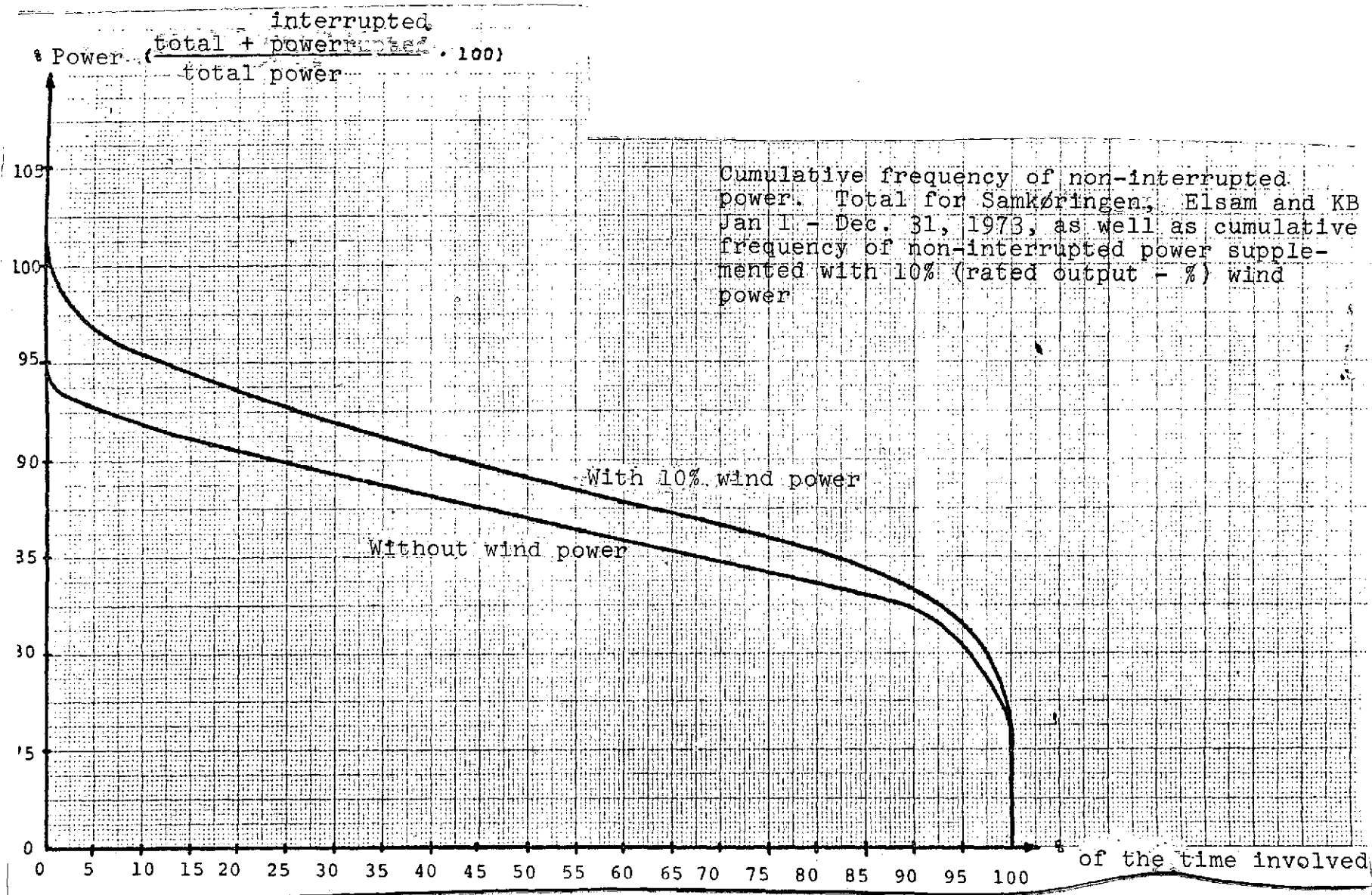


Figure 13



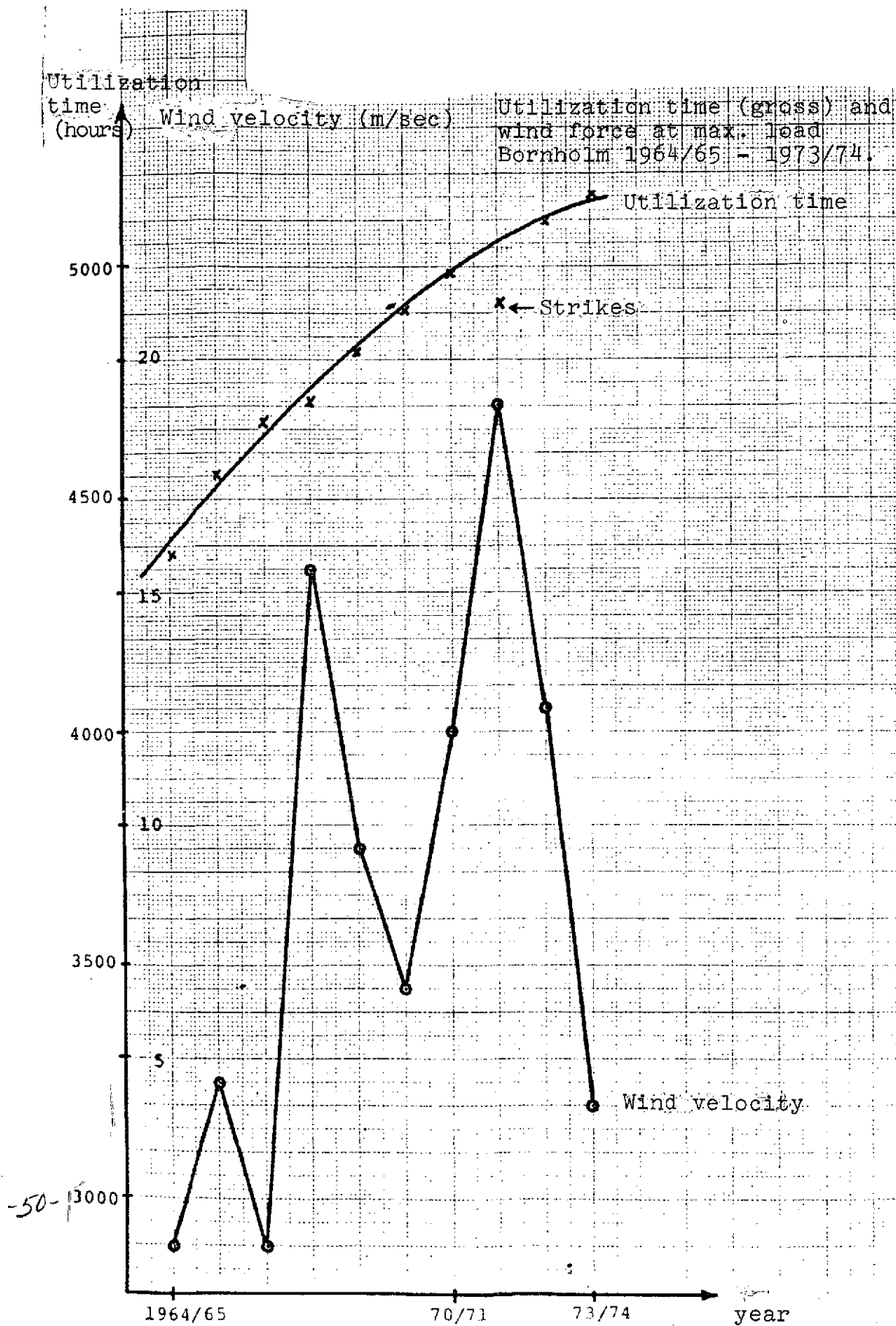


Figure 14